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RIVER AGGRADATION UPSTREAM OF A BARRIER

by

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A THESIS

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ABSTRACT

The primary purpose of the model study was to determine the effects of ponding of the flow on the river regime upstream of the dam, and the actual mechanisms involved in aggradation. The building of the regime slope of the bed by a uniform injection of sand into flow over a flat bed was also studied. A study was also made on the effect a sudden lowering of the water levels in a reservoir would have on the regime of a river.

The flume and related apparatus is described in detail. Methods of staining silica sand are also given.

It was found that the slope of the bed was built up by means of a moving sediment wave having the ideographic form of delta. The slope of the "topset bed" was the regime slope of the flow. The process of aggradation caused the final bed profile to have a slope equal to the original slope and the bed elevations raised by the amount of ponding. The degradation process caused the final bed profile to have a slope equal to the original slope and bed elevations lowered by the amount the water levels were lowered.

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CHAPTER I

INTRODUCTION

During the last several decades, the rate of industrialization of the North American Continent has increased rapidly. The geographical location of the centers of industry depends, to a large degree, on the proximity of the natural resources necessary to the industrial process. One of the main assets of any region, as far as industry is concerned, is the presence of a bountiful supply of water. The economy of a territory suffers if no adequate supply of water exists with which to attract the establishment of large manufacturing plants.

The necessity for water has led to the focusing of attention on rivers. The river flows, wasted if uncontrolled, are being harnessed by means of a dam. These dams are built, not only to supply water to industry and communities, but also to generate power, provide water for irrigation and satisfy many other secondary considerations.

The first dam designers had very little knowledge of the effects the dam would have on the river. It was tacitly assumed that the storage capacity of the dam was permanent, and that the river itself would experience no major detrimental changes. From the vantage point of several decades of observation, it is now generally conceded that these assumptions were erroneous, and that drastic changes in the conditions of the dam reservoir and the river, both upstream and downstream of the dam, are inevitable.

These alterations stem from the fact that the river carries a supply of sediment, both in the suspended and bed-load state. The mobility of the river bed allows the river to change its boundary conditions to compensate for any changes made in the original flow conditions. Thus, if through some method such as soil conservation or the construction of a dam the sediment load of the river is reduced, the river will proceed to reduce slope accordingly.

The reduction in slope is the result of bed scour below the dam with the consequent lowering of the water levels. The storage capacity of the dam will be reduced, not only by the deposition of the suspended fines carried by the water, but also by the deltaic extension of the river into the reservoir. This delta is built up by the deposition of the bedload near the entrance of the river into the reservoir, where the velocity of flow has been reduced. This extension of the river into the reservoir results in the aggradation of the river upstream of the dam, so that a slope is maintained adequate for the transport of the water-sediment complex.

As shown by the literature survey, it is evident that the problem of river reaction to the construction of a dam is being recognized and studied. This is especially true for the sedimentation within the reservoir. Since this phenomenon is so obvious and poses such grave problems, it receives the bulk of the attention. Further intensive study is given to the scour that will occur downstream of the dam. There is wide

divergence of opinion on the actual aggradation process upstream of the dam. This may be due to the fact that river reaction is usually quite slow, and thus is difficult to observe over short periods.

Conclusions regarding the aggradation phenomenon range from the belief that it does not occur any further upstream than the intersection of the maximum pool elevation and the original profile of the river, to the opinion that the final slope of the river will equal its original slope.

Since the aggradation process can have such a dire effect on the economy of the surrounding region, it would be profitable if the actual mechanisms and extent of the aggradation could be ascertained. For this reason, the writer, using a model, studied the reaction of the river to the ponding effect of a dam under idealized circumstances, i.e. with factors such as discharge, width, and sediment load held constant.

The equipment used in the laboratory did not allow for the formation of the delta that usually occurs in nature. The justification for the assumption that a simple raising of the flow in the model represented the conditions found in nature lies in the fact that the delta is merely an extension of the river and, as such, requires a slope. This slope will cause the water levels to rise at the point of entrance of the river into the reservoir. This raising of water levels is very similar to the imposed raising of the water levels in the model study, and thus the tests carried out in the laboratory are representative of actual field conditions, as far as the ponding up of water levels is concerned.

Other incidental effects studied in the model were; the processes of slope build-up under conditions of zero original slope and sudden injection of a sediment load, and the reaction of the bed to the sudden lowering of the water levels in its downstream end.

CHAPTER II

LITERATURE SURVEY

2:1 Reservoir Sedimentation

There is now a keen awareness of the problem of sedimentation within existing reservoirs with the consequent loss in storage capacity. This is exhibited in the large amount of literature available on the subject. The relevant articles are found in Bondurant (5)*, Fowler(9), Pariset (19), Einstein (8), Bondurant (6), Kenyon (15), Jones (14), Hemphill (11), Twenhofel (23), Kuiper (16), and Lane (17). The subjects covered by these authors are the different types of reservoir deposits, their characteristics, and the mechanisms by which they are laid down. Also included in these articles are methods by which the amount and position of deposition may be predicted, along with examples of measured volumes of deposited material in existing reservoirs.

Bondurant (5) states that the sand sizes will deposit out on the delta, while the silts and clays will form a blanket deposit on the bottom of the reservoir. The author's observation was that the ideographic form of delta, as described in Lane (17) and Twenhofel (23), could exist only in narrow valleys, since in wide valleys, the sediments tended to spread laterally. However, other three-dimensional effects reduced the chances of finding in any valley, the ideographic form of delta.

* Number in brackets refers to list of references at back of body of Thesis.

The major conclusions reached by Bondurant (5) are:

1. The sediments in the wide valley tended to project into the basin instead of spreading, with the spreading effect occurring due to avulsions.
2. Little meandering occurred on the deltas except for irregularities produced by avulsions.
3. The composition of the delta deposits was predominantly of the sand and clay sizes with a notable absence of silt sizes.
4. The bedding of the deposits was very complex; the sediment accumulation containing massive deposits of clay, and lenses of other material.
5. The sand deposits were highly erodible, while the deposits of clay were quite resistant to erosion.

Twenhofel (23) discussing the delta environment and its deposits, states that the delta composition includes the topset beds, the foreset beds, and the bottomset beds. The topset beds lie relatively flat and extend upstream of the delta front, while foreset beds lie at a steep angle approximating the angle of repose of the coarse sediment. Normal flow conditions produce the foreset beds while the topset beds are formed during flood conditions. The silt and clay sizes carried by the stream, form the bottomset beds. The bottomset beds will eventually become covered by the advancing front of the delta, thus creating a form of crossbedding. Lane (17) gives further information on the delta conformation from an engineering viewpoint rather than the geological approach that Twenhofel

used. The low velocities in the reservoir cause deposition, which in turn, causes further retardation of the flow so that the stream drops material further up the channel, thus creating the topset beds.

Fowler (9), discussing sedimentation processes, says that the river tends to flow in the pool as a concentrated stream along the old thalweg of the river. The fine sediment deposits out as a blanket formation on the floor of the pool while the coarser particles are deposited out before as a deltaic formation. The fine sediments are distributed over the reservoir floor by density currents which tend to follow the old thalweg of the river.

The author states that the deltaic formation is widened by the occurrence of avulsions and that the width of the delta tends to approach the meander breadth of the river. The author presents a method of calculating this width and the increase of projection of the delta into the pool. This method is based on the assumption that the delta is composed of coarse suspended sediment only. The method as formulated has as its factors: the total sediment load per day, the depth of the deposit, the ratios of the concentration of suspended sediment to the concentration of suspended sediment in the undisturbed river at the beginning and end of the reach in question, the time of deposition, the length of the reach, the average width of the deposit, and the unit weight of the material. Other factors affecting the location and volume of the delta are the flow characteristics, the sediment characteristics, and the channel characteristics.

Fowler (9) has assumed that since no bed load is present the

delta will be composed only of material that has dropped out of suspension. The description of the build-up of a delta from bedload only is given by Kuiper (16), who observes that in a wide valley, the momentum of the flow carries the stream out into the pool. At the outside edges of the stream, the friction between the moving and the quiescent water effects a reduction in flow velocity, which causes the sediment to deposit near the outer edges in the form of a ridge. These ridges, after consolidating at low flows, will act as guides for the high flows. More sediment is added and the ridge builds up, thus extending a finger-like deposit out into the reservoir. The resistance of these banks to erosion is dependent on the percentage of fine material they contain. Subsequent overtopping of these ridges will cause an avulsion, after which the old and new channels will share the flow. Since the old channel is probably curved while the new channel is straight, the sediment will tend to follow the old channel, because coarse material tends to follow the inside of a curve. This extra sediment in the old channel will enhance sedimentation here, especially since the new channel will have a higher slope than the old and will draw off more of the flow. In the case where both the old and the new watercourses have equal flows, aggradation will occur just upstream of the avulsion to such an extent that the channel will suffer another avulsion here.

Further comments on the conformation of deltas are given by Bondurant (6). In this study of the Conchas reservoir in New Mexico, the author mentions that the delta formation is very well defined, but that the topset beds do not extend any further upstream than the beginning of the computed backwater curve. The topset beds intersect with the

foreset beds at the maximum pool elevation. Maximum depths of deposits go up to 30 and 40 feet for the two different arms of the reservoir.

The author further states that the size of the material increased and the size range decreased with increasing distance upstream. The author observes that no material smaller than 30 microns remained on the delta while all material greater than 30 microns deposited on the delta. The density of the deltaic material varied directly as the depth under which it was buried. The author concludes that deltaic deposits seem to follow regular laws.

Furthermore, Bondurant (6) states, the depth of the blanket deposit in the reservoir was relatively constant with no variation of density with depth. However, the author concludes that the deposition of these sediments does not follow any definite laws.

Pariset (19), who primarily considered bedload, mentions that the factors affecting deposition are: the characteristics of the sediment, the flow and charge conditions, and the channel shape and slope. Contrary to what Bondurant (6) asserts, Pariset (19) concludes that the slope of the delta in the reservoir must be the same as the original regime slope, although possibly with minor variations due to different flow conditions. The author proposes a method of calculating the deposition, using Manning's "n", based on the assumption that the discharge is constant, the reservoir elevation is constant, the depth of flow is small as compared to the width of flow over the delta, the water profile of the reservoir is level in non-deltaic areas, and the river has a homogenous charge.

Einstein (8) summarizes the state of knowledge on reservoir

sedimentation and suggests possible areas of study as being the relation between the density of the deposits and flow conditions, the effect of flow conditions on the size gradation of the deposit, and the effect of unsteady flow on deposits.

The amount of sediment transported by rivers, and deposited in reservoirs, is staggering. This is especially true of rivers that flow through dry, arid, and denuded territory. Measurements of deposit volumes have been made, and the results reported by Hemphill (11), Bondurant (6), Kenyon (15), and Kuiper (16).

Hemphill (11) relates observations drawn from the investigation of several southwestern United States reservoirs. The author states that the annual sediment load in the Colorado river is 183,759,000 tons or 817 tons/sq.mi. of drainage basin, equalling about 0.84% by weight of the total flow. The Gila river is estimated to carry 1.46% by weight of its flow as sediment. The Rio Grande has a total sediment load equal to 1.41% by weight of its total flow, which results in a yearly deposition of 19,739 acre. ft. of sediment in the reservoir at San Marcial. The maximum bedload of this river is estimated to be about 25% of the total load. The author mentions that the Pecos river in Texas carries so much sediment that in 10 years the reservoir, Lake McMillan, had its capacity reduced by 42%. This corresponds to a yearly volume of 1225 acre-ft. or about 0.8% by weight of the total flow. An extreme example of the rate of sedimentation is a lake at Austin, Texas, on the Colorado river, which was filling up at such a rate that in 14 years the entire capacity of the

reservoir would be nullified, which was the case by 1931. The rate of deposition there was 3490 acre-ft. per year or about 0.09 acre-ft. per sq.mi. per year. The annual deposit in the Trinity river reservoir was 1,065 acre-ft. which corresponded to about 2.3% of its capacity. The average annual silt yield was calculated to be 0.57 acre-ft. per sq.mi. of drainage basin. The sediment load of the Pecos river varied from 2.13% by weight of the total flow in the upstream regions of the river, to about 0.43% by weight of the total flow in the downstream regions. Furthermore the author reports that in Lake Medina, 2,692 acre-ft. of sediment had been deposited in 13 years, which amounts to 207 acre-ft. per year or a yield of 0.35 acre-ft. per sq.mi. per year. In Lake Worth the annual deposition is 1,000 acre-ft. which represents a yield of 0.54 acre-ft. per sq.mi. giving the expected life of the reservoir to be 50 years.

Bondurant (6) gives some statistics on the rate of sedimentation in the Conchas reservoir in New Mexico. In this particular case, about 24,000 acre-ft. of sediment had deposited in the storage area in a period of 5 years. 80% of this volume was in the form of a delta while 20% of the sediment was deposited as a blanket over the bottom of the pool. Between 6 and 15 thousand acre-ft. had passed through the conduits in this time. Depths of deposits ranged from 30 to 40 feet.

A report on the silt load of streams found in the arid mountain regions in California is given by Kenyon (15). The sediment carried by these streams is in direct proportion to the flow so that the control of runoff will automatically control the sediment load of the stream. The

author reports that, in one instance, 88.2% of the flow was sediment.

To reduce the sedimentation of reservoirs, debris control structures have been built to intercept the sediment in tributaries and gullies feeding the main river.

2:2 Degradation Below a Dam

Although the reaction of the river bed below the dam was not studied in the laboratory, a brief summary of the literature available on the subject is included here because the topic is closely related to reservoir sedimentation and aggradation upstream of a dam.

Degradation occurs, as reported by Einstein (8) and Witzigman (24), when the silt-free flow below the dam proceeds to lower the slope of the stream to the value corresponding to the new conditions. Furthermore, as reported by Einstein (8) and Witzigman(24), the lack of suspended sediment in the flow prevents the river from rebuilding its sides after they have been eroded by the high flows. This results in the general widening of the river. However, Stanley (20) does not agree that this does occur.

There are generally many interfering factors present in the degradation process. As described by Einstein (8) and Stanley (20), the reduction in the maximum flow in the river may cause the bed to aggrade at the point of confluence of the main river and its sediment carrying tributaries. This is due to the fact that the sediment load of the river, derived from both the scoured bed and the tributaries, may be too high for the flow and the slope conditions and thus causes aggradation. Furthermore, Einstein (8) reports, the bed scour just below the dam may

remove only the fines in the bed material, thus causing a pavement to appear on the bed which reduces or eliminates further scour. Instances where scour has occurred in an unexpected manner are given by Borland and Miller (7), Stanley (21), and Witzigman (24).

Malhotra (18), Joglekar and Wadekar (13), and Ahmad and Ali (1) state that below a weir or barrage, the degradation occurs for only a short time, after which the bed proceeds to rise. This is due to the fact that the pool upstream of the weir will eventually be filled with sediment, thus allowing the transported sediment to pass the weir and deposit in the degraded reach. Stanley (21) gives an example of this occurrence in a large scale dam.

The retrogression, as described by Joglekar and Wadekar (13), is not limited to the main river only but may be transmitted to tributary streams.

Examples of the amounts of material scoured from the bed in the degradation zone are given by Stanley (21).

2:3 Aggradation Above the Dam

In the previous sections, the sedimentation within the pool and the reaction of the river bed below the dam to the imposition of the new conditions have been studied. Another matter of significance is the reaction of the river upstream of the dam to the new set of conditions. There is a variety of opinion on how far upstream the deposition will extend. These opinions range from the assertion that there will be no effect on the river bed beyond the limits of the backwater curve to the

belief that the river bed will eventually rise by the height of the obstruction all the way upstream until the effect is terminated.

Bondurant (5) reporting on a study of reservoirs, states that occurrences of deposition above the maximum pool elevation of the reservoir were rare. Any aggradation that did occur in the river bed upstream of the dam was primarily due to factors present previous to dam installation. In the case of Hoover dam, however, aggradation was stimulated by the erection of the dam. In another article, Bondurant (6) states that in the Conchas reservoir in New Mexico no aggradation above the upstream limits of the maximum pool elevation was observed. The main conclusion drawn by Bondurant (5) and (6) is that the deposition does not continue all the way upstream but is stopped within a relatively short distance from the reservoir.

The mainstream of opinion, at least on the North American continent, seems to be that the deposition will occur further upstream than the backwater reach caused by the ponding, but that the final slope of the river bed will be less than the original. Sugio (22) presents the results of a dimensional analysis of the deposition problem in combination with experiments run in a flume. The experimental analysis of the phenomenon leads to the conclusion that the final equilibrium slope will be a function of the original equilibrium slope, the discharge, and the sediment injection rate. The equation the author arrives at is as follows: $I_m/I_o = 0.272 (q s_o'/q)^{\frac{1}{2}}$, where I_m is the mean slope of the bed after sedimentation, I_o is the original slope of the bed before sedimentation, $q s_o'$ is the rate of sediment injection, and q is the

discharge. The author also states that the final slope = 0.0774 $(qso'/q)^{0.35}$. These two formulae are only applicable when the sand to water ratio is between $1.6 (10^{-4})$ and 12.3×10^{-4} , and the diameter of the sand grains varies from 0.844 to 0.89 mm.

That the aggradation does extend up the river beyond the backwater is verified in the article by Stanley (21). In this article, the author mentions that the aggradation above the Imperial dam on the Colorado river had progressed 55 miles upstream while the normal operating levels of the reservoir caused the water to back up only 15 miles. This is further affirmed by Stanley (20), who states that the aggradation will occur for long distances upstream depending on factors such as the slope of the stream, the size gradation of the transported particles and the charge of the stream. The author also states that the slope of these deposits will be less than the original slope of the stream. Another significant reaction of the river to the placing of the dam is that there will be increased meandering of the river in the aggraded reach. Joglekar and Wadekar (13) lend additional support to the view that the river will aggrade further upstream than the extent of the backwater effects, with the statement that the silting of the pool will cause the river bed levels to rise to the weir crest. The extension of this deposition upstream will not be confined to double the length of the pool but is usually much longer and will eventually affect the entire river, as well as increasing meandering in the aggraded reaches.

Bermel and Sanks (3) report on a model study made on a debris barrier located in California. Using different conditions of flow

representing the maximum flood conditions, and the design flood, along with a size, grading and amount of charge that conformed in model tests to the actual conditions found in the field, the authors found that the final slope of the bed ranged from 0.5 to 0.7 of the original slope. Their results were substantiated by prototype field conditions. Discussion by Amidon (2) of the paper by Bermel and Sanks (3), centered around the actual field occurrence of deposition in the debris barriers in California. In this discussion, the author states that deposition occurred over the total region between debris barriers and that the final slope of the aggraded bed was usually 0.7 of the original. He lists the variables in the problem as being the size and quantity of charge, the original channel slope, the discharge, the channel obstructions, and the period of years over which aggradation takes place. Further discussion on the problem of channel gradients above gully-control structures is given by Woolhiser and Lenz (25). In this article the authors state that the final slope of the aggraded reach will depend on factors that vary throughout the period of aggradation. The formula proposed is that $S_p/S_o = (G_{sp}/G_{so})^{5/7} (\psi_o/\psi_p)^{5/7} (Q_o/Q_p)^{6/7} (n_o/n_p)^{6/7} (b_p/b_o)^{1/7}$, where the subscript "p" indicates the final conditions and the subscript "o" indicates the original conditions, where S is the slope, Gs the unit weight of the bed load, ψ is an experimentally determined coefficient in du Boys equation, Q is the flow rate, n is the roughness of the channel, and b is the width of the channel.

Harris (10) explains why the final slope of the river after aggradation should be the same as the original slope of the river. The author describes the process of aggradation as follows: Initially, the

sediment deposits out in the pool created by the obstruction due to the lack of velocity. This deposited material causes the water to back up behind it so that the velocity in this region is lowered, causing part of the sediment to fall out here. This process continues to reproduce itself all the way upstream. Then the sediment once more deposits in the pool and the entire process recurs. In this manner the river will finally have lifted itself up parallel to the original bed and will have a slope identical to the original slope. The author states the influencing factors to be breadth changes with changes in elevation due to the trapezoidal cross-section, the variability of discharge, and the variations in the charge as concerns the size, specific gravity and amount of the sediment. The theory of parallel aggradation is substantiated by Malhotra (18), who reports that the usual reaction of a river to the placing of a barrage or weir across the channel is the flattening of slope as the deposition heads upstream. This action is followed by a restoration of the original slope so that finally the stream levels are raised by the height of the obstruction. Furthermore, Pariset (19) states that the deltaic extension of the river has a regime slope and that the occurrence of silting in the upstream region of the river depends on the time elapsed and the sediment charge.

Johnston and Minaker (12) explain the occurrence of slope ratios less than unity. The authors state that the deposited material is finer than the original bed material because both suspended load and bed load are deposited. This results in a lower equilibrium slope than that required for the coarse material. The supply of coarse material is so low that the original slope of the stream is not reached for a long

period of time. This time is shortened, however, by the fact that the trapezoidal channel gives a greater width with smaller depth. This reduces the sediment carrying power of the stream and thus requires a greater slope to transport the sediment than at a smaller width. Kenyon (15) reports that the storage capacity of debris barriers in California includes deposition above the dam. This deposited material is designed to have a slope equal to, or greater than, the original slope of the stream. There is one case reported, states the author, where the channel was found to have lifted itself up parallel to its original profile. If this effect is not considered in the design, the river may lift itself out of its bed and seek an entirely new channel.

The effects of channel aggradation are listed in Jones (14). The author states that the flood levels of the river will be raised, thus increasing the frequency of the inundation of the surrounding farmland. This flooding will result in the deposition of infertile sediment over the land, thus reducing its productiveness. The drainage of the territory surrounding the river will be impaired, resulting in the raising of the water table.

Borland and Miller (7) found that the problems arising from the aggradation process were the impairment of the drainage of the area, and the deterioration of the channel. The authors state that where the groundwater table had risen to an elevation near the ground surface, corrections were made by dredging channels and developing cutoffs to induce bed lowering. The channel deterioration was arrested through the use of the channel straightening and alignment, rip-rapping of the

banks of the river and the use of river training works and levees.

CHAPTER III

EQUIPMENT AND OPERATION

3:1 Introduction

The equipment, as depicted in PLATES 1, 2, 3, consisted of a plexiglass flume, a sediment injection system, a flow circulation system, a measuring and recording device, and other miscellaneous items related to the above.

3:2 The Flume

The flume was 105 ft. long, 16 inches wide, and 13 inches deep. The framework of the flume consisted of aluminum angles placed at the top and bottom, and running the length of the flume. All joints were coated with a silicone rubber sealant to prevent leakage. The flume rested upon externally threaded iron pipes spaced at five foot centers. These stands were attached to the floor and were provided with threaded rings which supported an iron piping crossbar.. This crossbar on which the flume rested, could thus be raised and lowered to any desired elevation by adjusting the threaded rings. On the stands, just above the flume and running the length of the flume, were level rails on which the measuring device rode.

3:3 The Flow Circulation System

A pump, operating under five feet of head, circulated the discharge from the outlet box to the inlet box. The outlet box, though serving as a flow receptacle, also trapped the sediment that was carried

out of the flume by the water. The downstream end of the flume was equipped with stoplog slots. The elevation of the water surface could be adjusted by inserting stoplogs having the desired depth. The outlet box, $7\frac{1}{2}$ feet long, $3\frac{1}{2}$ feet wide, and 3 feet deep, was equipped with a 90 degree weir for flow measurement. A control valve was installed in the line to allow adjustments in discharge. The pump, the outlet box and the inlet box were equipped with drains for the replacement of the water supply.

3:4 The Bed Material

A silica sand, locally known as Peace River glass sand, was used as the sediment in the flume. The original grain size analyses were carried out with the use of sieves, but this method was soon abandoned in favour of the visual tube method of analysis. The visual tube method showed a different grain size distribution for the fine size range.

3:5 The Sand Injection System

A constant sand supply was maintained using a Syntron sand injector. This apparatus consisted of a conical hopper with a three cubic foot capacity, and a vibrating tray. Provisions were made to spread the concentrated stream of dry sand uniformly over the width of the flume. It appeared that the dry sand, when fed into the main stream, would not integrate with the flow. This problem was solved with the use of an intermediate tray on which both a small stream of water and the dry sand was fed, thus mixing the two components satisfactorily.

3:6 Provisions for Reuse of Sand

The sand that collected in the outlet box was washed through the

drain into a settling pool at a lower level. It was then removed for colouring, drying, sieving and reuse.

3 7 Sand Colouring Methods

To facilitate the tracing of the deposition upstream of the barrier, differently coloured sands were used. Preliminary research into staining methods indicated the possible usage of several dyes, all of the biological stain variety. The stains found to be effective were; methyl violet, which yielded a deep purple colour; methylene blue, which imparted a dark blue colour to the sand; and malachite green, which gave the sand a turquoise colour. Only a short period of time was required for all the colour contained in the water solution of the dye to be transferred to the sand. The resulting tint was indelible to a high degree, although a bit of colour was transferred to the water after long running periods. Preliminary abrasion and soaking tests were carried out to ensure that the stain was permanent.

It was learned¹ that another biological stain, the aniline dye, Sudan III, would also be suitable for staining purposes. This dye, however, required the use of a volatile hydrocarbon as the solvent. Benzene was advised as being the most suitable, but the compound acetone was also tried. Acetone did not have the dissolving qualities that benzene had and thus benzene was used. The resulting colour, a bright red, was satisfactorily indelible, although not to the extent exhibited by the previously mentioned dyes.

Indicators, such as methyl red, methyl orange, thymol blue, and cresol red, were also tested, but proved to be wholly unsatisfactory since

¹E M. Laursen, Professor of Civil Engineering, University of Arizona. Personal communications.

the dye did not adhere to the sand particles.

3:8 Sand Drying Procedure

Since the sand injection system operated only with dry sand, the dyed reclaimed sand was put under gas heaters to bring it to a moisture content at which no coherence of particles occurred. It is unknown if the moisture content of the reclaimed sand was identical to the moisture content of the sand as originally purchased and used at various times throughout the test. Dyeing with the red stain did not require further drying with the heaters since the volatile benzene evaporated rapidly.

3:9 Measuring Equipment

Water surface and bed elevations were obtained using an electrically powered plotter connected to a Mosely recorder. This apparatus consisted of: a probe which could be set to follow the bed a given distance above it; and an electrical drive motor. (Ref. 26) A combination of servo-motor transmitted electrical impulses, indicating location and elevation of the probe, to the recorder which subsequently interpreted these impulses in terms of movements of the pen on the paper. Adjustment to the equipment allowed the probe to follow either the sand-water interface, or the air-water interface, thus giving plots of both the water surface elevations and the bed elevations. Water surface elevations were not obtained with the plotter for the first 550 hours of operation. During this period, water surface elevation data were obtained by the use of a point gauge.

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CHAPTER IV

TESTING PROCEDURES

4:1 Preliminary Calculations

To obtain insight into the slopes that could be expected, preliminary tests were run using a plexiglass flume, a velocity meter, and a sand bed. The zero bed factor, i.e. the term, V^2/d , when there is vanishingly small charge, was found to be approximately 1.5. The regime equations of Blench (1), with the desired depth, width, charge, as 3" inches, 16 inches and 10 respectively, and the zero bed factor of 1.5 as found in the test, gave the flow as 0.3 c.f.s., and the bed slope as 0.33% which could be handled in a level flume, without spill.

4:2 Initial Running Conditions

Before testing, the flume and the rails for the plotter were leveled. The rails provided a datum for the plotter, so that the slopes given by the plotter would be a true representation of the actual slope of the river bed.

A sand bed of two inches thickness was placed in the flume. The purpose of the level sand bed was to allow the river to build up its own slope from the injected material and allow observations of this process. This period of slope building also provided time to check the operation of the equipment and to obtain experience in running it.

In this initial running period, inadequacies in the sand injection system caused frequent stoppages of the sand flow. These stoppages

resulted from a lack of mixing of the sand and water in the intermediate tray, with the resultant blockage of the vibrating tray. Minor changes to the apparatus solved these problems. A more serious problem occurred when the unstable platform allowed the variation of the weight of sand in the hopper to have a strong effect on the sand flow rate. This difficulty was overcome by weighing the platform down with 100 pounds of lead. The sand flow rate after these difficulties were overcome corresponded to a charge of 9.2, and remained virtually constant for the entire testing period (See FIGURE 1).

The standard published calibration for a 90 degree weir was accepted for the weir used. The flow in the flume was maintained at 0.3 c.f.s.

4:3 Measurement Procedures

The initial recordings given by the plotter were very erratic because of the well-developed dune formation of the bed. Smoothing out of the bed elevation plots was achieved by installing a capacitor on the recorder. The elevation of any point on the resulting profile was an average of the previously sensed elevations. Furthermore, a considerable lag occurring between the time the plotter sensed an elevation and the time this elevation was recorded was inherent in the system. Thus the charts derived when the plotter travelled downstream indicated higher elevations than when the plotter travelled upstream. This factor did not influence the results since the direction of the plotter traverse was alternated each run; in the analysis of the data, the smoothing curves followed the average elevations of consecutive runs. However, occasionally the measuring equipment broke down, resulting in erratic and unreliable data.

4.4 Slope Buildup Test

The purpose of the first test was to determine the mechanism of slope building in a river. During this first test period, lasting approximately 600 hours, the undesirable characteristics of the equipment were detected and eliminated.

4.5 1 Inch Ponding

As soon as the bed had reached an equilibrium slope, the water surface was ponded up 1 inch at the downstream end. This proved to be an excessive amount, since the water surface recordings showed the backwater curve to extend over the total length of the flume. Since this did not conform to the conditions under investigation, i.e. sedimentation upstream of the backwater curve, the water surface was subsequently lowered to the original value and the bed allowed to reach its former equilibrium state.

The use of red-coloured sand was commenced at the time of the initial ponding. The expected results of the introduction of coloured sands did not materialize. It was assumed that the sand would traverse the length of the flume and deposit out in the downstream end as a result of the aggradation process. Actually, the sand became caught up in the dune activity, causing the sand bed to attain a coloured layer extending to the depth of the deepest trough. The bottom of the coloured layer was a perfect straight line. The distance this colouring had travelled downstream depended on the period of time that the sand had been added.

4.6 Initial $\frac{1}{2}$ Inch Ponding

As soon as the river had again attained equilibrium, the water

was ponded up once more but only by $\frac{1}{2}$ inch. From FIGURE 2 it can be seen that approximately 45 feet of the upstream portion of the river was unaffected by the backwater curve; this amount being sufficient for the study of the aggradation process. During the latter part of this test difficulties with the recorder occurred and the reliability of the recorded bed levels is questionable. Just before the end of this test the error was found and corrected, so that some data on the equilibrium condition attained by the flow are available.

At the time the water was ponded up $\frac{1}{2}$ inch, blue sand was substituted for red to facilitate observation of the amount of aggradation. The use of coloured sand made it possible to see if the dune height varied with distance downstream.

4:7 Second $\frac{1}{2}$ Inch Ponding

Immediately after the river had reached equilibrium at the higher bed elevation the water was again ponded up $\frac{1}{2}$ inch, resulting in renewed aggradation. During this test, the plotter and recorder gave no trouble.

At the beginning of the second aggradation run, the original white sand was again used. As soon as the white sand layer reached the downstream end of the flume four differently coloured layers existed; white, red, blue, and white (See PLATE 4). The bottom white layer was the undisturbed part of the bed while the thickness of the red layer represented the aggradation due to the initial $\frac{1}{2}$ inch ponding. The thickness of the blue layer represented the aggradation due to the second $\frac{1}{2}$ inch ponding while the depth of the white layer represented the dune amplitude.

4:8 First Degradation Run

After the bed had reached equilibrium under the conditions of the second aggradation test, the water levels were lowered $\frac{1}{2}$ inch at the downstream end. The water surface elevations for Stations 6, 7, and 8 are too high since the plotter did not function properly when the probe operated at this height.

4:9 Second Degradation Run

After the bed had reached equilibrium at the lower elevations, the water levels in the downstream end were again lowered by $\frac{1}{2}$ inch. During this test, the measuring equipment gave consistent and dependable data on the water surface elevations.

4:10 Sand Sampling

The deviations from the ideal log-normal distribution in the original material (see FIGURE 3) were soon eliminated (See FIGURE 4) as the original material became bedload. The sand samples were analysed for the first two months to detect variations occurring in the grain size distribution with respect to time and position in the flume.

The grain size analyses obtained are on file at the Department of Civil Engineering of the University of Alberta. Also on file are the original recorded bed and water surface profiles.

CHAPTER V

METHOD OF ANALYSIS

Initially the charts obtained from the plotter were superimposed on each other to facilitate the observation of bed level changes. Since the profiles were quite irregular because of the dunes, average slope lines were drawn in by eye. The combination of these average profiles indicated the various reactions of the bed. The variations in the plots due to the waviness of the rails supporting the plotter, and the dune activity, ruled out any observation of effects limited to a small part of the bed. As the aggradation process was occasionally limited to a small section of the river the elevations of the bed at certain stations were obtained from the charts and plotted versus time. Although a large amount of scatter was present it was possible to draw smoothing curves through these points. (See FIGURES D1(A-E)).

The smoothing curves of FIGURES D1(A-E) have been superimposed in FIGURE 5. The amount the rails deviated from a chosen datum was measured at each station and this value was then incorporated into the relative positioning of the curves. However, this process did not wholly eradicate the distortions.

The smoothing curves did not follow the plotted data in some areas since these points were in error due to deficiencies in the equipment. The aggradation and degradation runs showed definite trends; therefore, although the data were unreliable at critical

times for several stations, the smoothing curves here were adjusted with these trends in mind. The plots were not adjusted to ignore valid data, but estimated in areas of insufficient and erratic data.

The slope lines of FIGURES 6, 7, 8, 9 and 10 were obtained by plotting the elevations versus stations at a certain time from data obtained from FIGURES D1(A-E). This method produced slope lines which showed the trends much better than did the original charts. The water surface plots were likewise obtained (see FIGURES 11, 12, 13, 14, 15 and 16) from FIGURES 11 and D2(A-C).

Initially the median grain size was derived from plotted grain size distribution curves. However, a different method was used in the case of the charts obtained with the visual tube method of analysis. (see Ref. 27). This apparatus transfers a curve onto a chart which indicates the size range of the sample and the relative position of a particular grain size within the sample. The height of this curve above a constant base is determined by the size of the sample. The grain size midway up the curve is the median grain size of the sample. The diameter of this particle size varies as the distance from the point on the curve to the right hand edge of the chart. This distance was measured and applied to a graph which correlated the distance from the edge of the chart to the grain size (see FIGURE 17), thus yielding the median grain size of the material.

CHAPTER VI

DETAILED OBSERVATIONS

6:1 Slope Buildup

Initially the injected sand was deposited in the form of a wedge. This shape was preserved for approximately 50 hours, after which it developed into a formation having the ideographic form of a delta (see PLATE 5 and FIGURE D3). This configuration, with minor variations, persisted throughout the period of slope building. The slope of the "topset bed" remained constant for the period of slope building and was equal to the equilibrium bed slope. FIGURE 6 shows the profile of the bed at various times during the slope build-up process.

Upstream of the front of the sediment wave , the bed load movement was apparent, while down stream of the front there was negligible bed load transport. The active section of the bed is shown in PLATE 6. Although the bed downstream of the front remained inactive, the dunes that were present were formed previously. Some of the injected sand was used to supply the advancing dune front, while the remainder deposited out uniformly over the length of the "topset bed". FIGURES 5 and 6 with the corresponding water surface plots, FIGURES 11 and 12, show in various ways the type of changes in the profile that occurred. FIGURES 5 and 6 show the bed at a certain section to remain inactive until the advancing sediment wave reached that section, whereupon the bed rose suddenly and then slowly elevated to equilibrium, somewhat similar to the case

for a water wave. It can be seen that the upstream sections continued to rise until the advancing front reached the downstream end. It is interesting to note that all the stations, except the last two, reached equilibrium when the advancing sediment wave reached the stoplogs. At this point, the first 80 feet remained stable while the downstream 20 feet continued to rise to equilibrium.

The volume of sand used in forming the sediment wave was calculated from FIGURE 6. This volume was then compared to the amount of sand injected as derived from FIGURE 1, Table I and FIGURE 18 indicate an error of 2.3%. However, the errors at intermediate stages of sediment wave advancement were of a higher order with large discrepancies between sand inflow and volume increase occurring during small time intervals. TABLE II shows data, derived from the daily charts, used in the calculation of the rate of advancement of the sediment wave. It can be seen from this table, and from FIGURE 19, that the rate of advancement fluctuates wildly. The scatter of the points allows only a highly unreliable best-fit line to be drawn.

A logical analysis of the process would lead to the conclusion that the wave front must initially have a relatively large rate of advancement, since a high percentage of the injected sand would be deposited in the foreset bed of the wave. As the formation became longer, however, the amount of sand available to lengthen the wave would have become progressively smaller, as more of the sand would deposit over the length of the "topset bed". FIGURE 19 shows just such a trend up to about station 6. After this point, however, the rate of advancement rose

to values higher than those expected. Since TABLE I and FIGURE 1 show no large variation in the rate of sand injection, the reason for the inordinately high rate of advancement of the wave front cannot be explained. It may be added that for various periods during the earlier part of the test, there was no charge due to defective equipment. The resumption of sand injection merely served to fill in the scour hole caused by the sediment free flow. These variations may account for some of the scatter about the best fit line, but not for all of it.

TABLE II and FIGURE 20 indicate the variation of the height of the wave front with distance traversed and show that the front height became slightly less as the wave moved downstream. The points indicating front height in the extreme downstream regions are unreliable because the short length of inactive bed prevented the measuring equipment from recording an accurate dune shape.

The bed elevations in the downstream 20 ft. rose after the rest of the bed had reached equilibrium. This condition does not correspond to expectations since, logically, if there is to be any rise at all, it should involve the total length of the bed and be due to ponding.

The reasons for the upward trend in the rate of advancement of the wave front in the latter portion of the flume, may be the decrease in dune height near the downstream end of the flume. A very significant factor influencing the data obtained in the first several hundred hours is the unreliability of the plotter as far as calibration and reproducibility is concerned. Until a final calibration was devised after 680 hours of operation, the slopes obtained were somewhat undependable. The calibration of the plotter could only be estimated roughly from manual measurements and visual observations. The previously mentioned capacitor

was not installed until 370 hours of operation had elapsed. Consequently, the data taken previous to this time showed every small variation in the bed. (See FIGURE D3)

6:2 First Aggradation Run

As soon as the equilibrium slope had been reached the water was ponded up $\frac{1}{2}$ inch. This figure is approximate due to the imprecise stoplog arrangement.

The initial reaction of the bed is shown in FIGURES 5 and 7. A sediment wave caused the downstream region of the river to rise slowly as the wave travelled upstream. The slope of the reach over which the wave had passed was slightly less than that of the original bed. As soon as the wave reached the upper end of the flume, the aggradation here became rapid, while the deposition at the lower end of the flume ceased. This aggradation process stopped when the slope was slightly less than the original slope. The bed then entered into a state of quasi-equilibrium which persisted for only a short period, after which the bed resumed aggradation in a manner similar to that described above. As seen in FIGURE 7, the activity was rapid and did not cease until the bed elevations in the downstream end remained constant. Some variations to this trend occurred in that the upstream end rose slightly more before the final elevation of the downstream end was reached. As soon as the lower region of the river had reached an equilibrium position, the upstream portion of the river began to aggrade. This process continued until equilibrium was attained over the length of the river.

The effects described above are also shown in the plots of watersurface profiles, (FIGURES 11, and 13), which show that as the bed commenced to rise in the region of the backwater curve, a corresponding effect is evident in the changes in the water surface profile. The deposition caused the flow to pond up, which in turn caused more material to deposit out further upstream. All of the injected sediment does not deposit at the wave front, since the disturbed reach downstream of the front continued to rise.

As shown in FIGURE 13 the advancement of the sediment wave upstream caused a corresponding backwater effect. The presence of this backwater effect in the upstream end may have caused most of the injected sediment to deposit out there with progressively smaller amounts depositing out further downstream. This may have caused the bed to reach the equilibrium slope at intermediate elevations. However, it cannot be explained why the bed then remained in a state of quasi-equilibrium.

The initial wave travelled the length of the flume at a rate of 1.77 feet per hour. The slope of the disturbed reach remained constant during the period of traverse.

As can be seen from FIGURE D1 (A-E), much of the data showing the second sequence of bed rise indicates a low bed elevation. The first few points show that the bed had risen, but the following data shows the bed to have gone down again. These points are believed to be in error since at that time the plotter failed to function properly. These undependable data lend a degree of uncertainty to the precise mechanism of aggradation, but do not invalidate the trends observed.

As in the case of all the data obtained from the plotter, the

height of the dune formation of the bed was several times greater than the height of the disturbances produced by the ponding. This causes some of the scatter of the points about the smoothing curve.

6:3 Second Aggradation Run

This test, in which the water was again ponded up $\frac{1}{2}$ inch, was begun after the bed had reached equilibrium following the first aggradation run. The river bed reaction, was a sediment wave moving upstream. The slope on the back of the wave was constant, although less than the original equilibrium slope of the stream. The upper regions then proceeded to rise after the wave had reached the upstream end. The result of this process was that the bed throughout the length of the flume, reached a slope similar to its original slope but at an elevation less than $\frac{1}{2}$ inch above the original equilibrium profile.

The bed remained at this intermediate stage for a relatively long period of time, during which there occurred no significant changes in the bed. This phenomenon does not conform to the expected behaviour. No explanation can be given to account for the inordinately long period of time during which the bed profile remained unchanged.

After this period of quasi-equilibrium, the bed resumed aggradation. This process did not conform to the procedure that occurred when the initial wave travelled upstream. In this final stage of aggradation the initial deposition occurred in the center section of the flume, with the downstream and upstream ends retaining constant bed elevations. (See FIGURE 8). Then the downstream end aggraded until most of the bed except the upstream end had reached final elevations. Finally, the upstream reach rose to final

elevations, at which state the entire bed had achieved a final slope equal to the original slope but with bed elevations higher than original elevations by approximately $\frac{1}{2}$ inch.

The data giving the water surface elevations can be seen in FIGURES 11 and 14, which show that there is no data for a large reach in the upstream region. This lack of data, due to the limitations of the plotter, detracts considerably from the usefulness of the profiles shown. However, the limited data do not contradict the observations made of the bed activity.

The second test compares fairly well with the results of the first test, although some differences are noticeable. One of the differences is that the initial rate of rise is much higher in the second test than in the first. Furthermore, the intermediate period of quasi-equilibrium was longer in the second test than in the first. Also, the final stage of aggradation was concentrated initially in the downstream end in the first test while in the second test the initial deposition in the final stage of aggradation occurred in the central regions of the flume.

The data for the second aggradation run as presented in FIGURES D1(A-E), are more accurate and reliable than the data for the first aggradation run. However, it was difficult in some cases to determine the time at which the sharp rises in the bed took place.

6:4 First Degradation Run

As soon as equilibrium conditions were achieved after the second aggradation run, the water level was lowered $\frac{1}{2}$ inch. The reaction of the

bed can be seen in FIGURES 5 and 9.

FIGURE 9 shows that a negative wave was formed immediately after the water level was lowered. This wave travelled upstream at a relatively high rate so that in 15 hours it had reached the upper end of the flume . During this period, the bed in the disturbed region of the flume continued to lower. The amount of degradation varied inversely as the distance upstream, thus giving a higher slope than the equilibrium slope after the second aggradation run. This slope continued to increase as the wave moved upstream.

As soon as the wave reached the upper end of the flume, the total length of the bed was subject to degradation, which was slightly concentrated in the downstream region, until approximate equilibrium was reached at the downstream end of the flume. Then, with the rate of degradation in the downstream portion of the flume greatly reduced, the process in the upstream region was enhanced. Varying rates of degradation occurred throughout the length of the bed until a slope had been reached equal to the original slope.

The corresponding changes in the water surface profiles can be seen in FIGURES 11 and 15. These figures substantiate the bed observations.

The reliability of the data on the river bed changes is relatively good. There is little scatter of the plotted points about the smoothing curve. However, the waviness of the rails over which the plotter travelled was largely to blame for the peculiar bends in the slope lines. A correction for this waviness was incorporated in the data without taking into account the variation of this waviness with time. The wavy condition made it difficult to ascertain the true slope of the bed and thus caused difficulties in determining precisely the actual degradation process.

6:5 Second Degradation Run

As shown in FIGURES 5 and 10, the wave that travelled the length of the flume appeared in this test also. Approximately the same period, i.e., 15 hours, was taken in the traverse of the wave. The degradation over the part of the bed downstream of the negative wave caused the bed to lower itself such that it was generally parallel to its original position. This parallel degradation continued until the wave reached the upstream end, after which the entire length of the bed degraded uniformly.

This parallel sequence of degradation continued for a period after which the degradation in the lower regions accelerated slightly until the bed there reached an elevation near equilibrium. Meanwhile, the bed in the upper regions continued to degrade until this reach also attained equilibrium conditions, so that the slope became stabilized at a value approximately equal to the original equilibrium slope, but with the bed at a lower elevation.

The figures depicting the changes in the water surface profiles, (FIGURES 11 and 16) show approximately the same effects.

The difference between the two degradation tests occurred when the wave had just reached the upstream end. In test one, the ensuing degradation was slightly concentrated in the downstream region while in test two, the scour action produced parallel profiles.

6:6 Sand Sampling Tests

FIGURE 3 shows the grain size distribution of the original material, while FIGURE 4 shows the grain size distribution of the sand, as found with a sieve analysis, after the sand had been subjected to the washing action of the

flow. It is evident that after acting as bedload, the sand followed the log-normal distribution very closely. FIGURE 3 also shows an analysis of the sand using the visual tube. Although not shown, the results from the visual tube in the finer sizes are slightly different from the sieve analyses; however, they can be used for comparative purposes.

From FIGURE 21, it is evident that the average grain size of the sand did not vary significantly with position in the flume. FIGURES 2(A-C) show that the grain size at a given station did not vary extensively with time. In summary, it can be stated with reasonable certainty that the sand had a log-normal distribution which did not vary with time or position in the flume.

6:7 Coloured Sand Usage

The coloured sand was used with the idea that it would give an indication of where the sediment would deposit in the downstream regions when the water surface was raised. The actual occurrence was that the coloured sand mixed with the existing sand. Thus, soon after the commencement of sand injection, a layer of sand existed with its colour concentration and length depending upon the period of injection. The colour of the sand graded through about 30 feet from the pure final colour to the pure original colour. The time taken to reach the pure final colour throughout the length of the flume, was from 10 to 15 days. An example of the colour gradation and the layer effect of the injected sand can be seen in PLATES 4 and 7.

As can be seen from FIGURE 23, the slope of the differently coloured sand interfaces was equal to the original equilibrium slope of the bed. Although these slopes indicate a relatively constant dune

amplitude, this is only apparent since the interface is due to the action of the deepest troughs. The actual occurrence was that the maximum dune amplitude was constant throughout the length of the flume.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7:1 Conclusions

From the preceding observations and discussions, the following conclusions may be reached:

1. Referring to Section 6:1, it can be seen that the slope of a river is built up by means of a sediment wave which travels from the point of sediment injection to the control point downstream. The slope of the back of this wave is constant throughout the traverse of the wave and is equal to the equilibrium slope of the stream.

2. Sections 6:2 and 6:3 show that aggradation after ponding up at the downstream end occurs by means of a sediment wave travelling upstream. The slope of the disturbed area of the river during the traverse of the wave is lower than the original equilibrium slope. The cases of flatter slopes observed in nature probably represent this condition and would indicate that equilibrium is not yet reached. An intermediate equilibrium slope is then attained by means of differential aggradation, the largest rate of aggradation occurring in the upstream region of the flume. This intermediate stage persists for a period during which no further aggradation is experienced. As soon as this period of quasi-equilibrium ceases, the downstream region of the bed rises sharply while the upper end of the river remains stable. As soon as the aggradation at the lower end of the flume causes the bed to rise to within approximately final elevations, the upstream region begins to rise to equilibrium. At equilibrium, the bed has a slope identical

to the original slope, and with bed elevations increased by the amount of ponding.

3. It can be seen from Sections 6:4 and 6:5 that the lowering of the water surface causes a negative sediment wave to travel upstream. The passing of the wave leaves a slope higher than the original, which is held throughout the subsequent parallel degradation. After this phase of uniform scour, the rate of degradation is accelerated slightly in the downstream regions while remaining fairly constant in the upstream areas. Since the bed in the lower end reaches equilibrium before the upper extremities do, final degradation continues in the upstream regions. This equilibrium condition consists of a slope equal to the original equilibrium slope, and with the entire bed having elevations lessened by the amount the water surface has been lowered.

4. The tests indicated that aggradation occurs beyond the initial upstream end of the backwater curve, as well as the maximum reservoir elevations, contrary to the belief expressed by several authors.

7:2 Recommendations

The experience of running these tests enables the writer to make certain recommendations. These include:

1. Changes in the dimensions and rate of movement of the sediment wave in the slope building process should be studied with respect to variations in the charge and discharge.

2. The wave effects involved in the degradation and aggradation processes should be studied more thoroughly using better equipment.

3. In reference to item no. 2, the variation of the wave height due to variations in flow, charge and sediment characteristics should be studied. This would be necessary as in the conditions found

in the testing, the height of the dunes was of a larger order than the disturbances introduced.

4. To increase the accuracy of the tests it is recommended that a longer flume be used so that the amount of ponding will be of a higher order than the height of the dunes on the bed.

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- 7 48
26. Bed Level Plotter-Meander Area, Instrument Section Technical Memorandum, Department of Scientific and Industrial Research, March, 1961.
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APPENDIX A

TABLES

TABLE I
INJECTED VOLUME OF SAND DURING SLOPE BUILDING TESTS

I		II	III	IV	V
TIME IN HOURS From To		VOLUME OF SAND INJECTED Ft ³	CUMULATIVE AMOUNT -Ft ³	VOLUME OF SAND AS FOUND FROM Fig. 6 Ft. ³ CUMULATIVE VOLUME Ft ³	
0	25	1.49	1.49	1.84	1.84
25	50	1.49	2.98	1.34	3.18
50	75	1.64	4.62	1.31	4.49
75	100	1.65	6.27	1.83	6.32
100	125	1.56	7.83	1.06	7.38
125	150	0.90	8.73	1.34	8.72
150	175	1.58	10.31	1.15	9.87
175	200	1.62	11.93	1.33	11.20
200	225	1.59	13.52	1.15	12.35
225	250	1.53	15.65	1.60	13.95
250	275	1.53	16.58	1.33	15.38
275	300	1.55	18.13	1.99	17.27
300	325	1.68	19.81	2.38	19.65
325	350	1.60	21.41	1.64	21.29
350	375	1.47	22.88	1.89	23.18
375	400	1.62	24.50	1.66	24.84
400	425	1.65	26.15	1.93	26.77
Difference between final values in Column III and Column V is 0.62. Ft ³					

TABLE II

RATE OF DUNE TRAVEL

I	II	III	IV	V	VI
Time - Hrs.	Distance Dune Downstream in Ft.	Height of Dune Front in inches	Time Increment in Hours	Distance Increment in Feet	Rate of Travel Ft/Hr.
6	5				
21	10	1.7	15	5	0.333
27	12	1.3	6	2	0.333
31	13	1.4	4	1	0.250
49	18	1.3	18	5	0.278
56	19	1.5	7	1	0.143
72	24	1.6	16	5	0.312
79	26	1.2	7	2	0.286
98	31	1.4	19	5	0.264
107	35	1.4	9	4	0.445
121	37	1.2	14	2	0.143
151	45	1.3	30	8	0.266
157	45	1.2	6	0	0
175	49	1.0	18	4	0.222
182	49	1.0	7	0	0
199	52	1.1	17	3	0.176
205	54	1.2	6	2	0.333
223	57	1.2	18	3	0.167
230	57	1.0	7	0	0
252	60	1.0	22	3	0.136
270	66	0.9	18	6	0.333
320	72	1.3	50	6	0.120
365	80.0	1.2	45	8.0	0.178
389	89.0	1.0	24	9.0	0.375
396	90.5	1.1	7	1.5	0.214
410	94.5	1.1	14	4	0.286
417	95.0	1.2	7	0.5	0.071
434	97.0	1.2	17	2.0	0.118
482	102	1.3	48	5.0	0.104
488	104	1.4	6	2.0	0.333
508	105	2.0	20	1.0	0.050
513	106	-	5	1.0	0.200

APPENDIX B

FIGURES

FIG. 1
VARIATION OF SAND
FLOW RATE WITH TIME

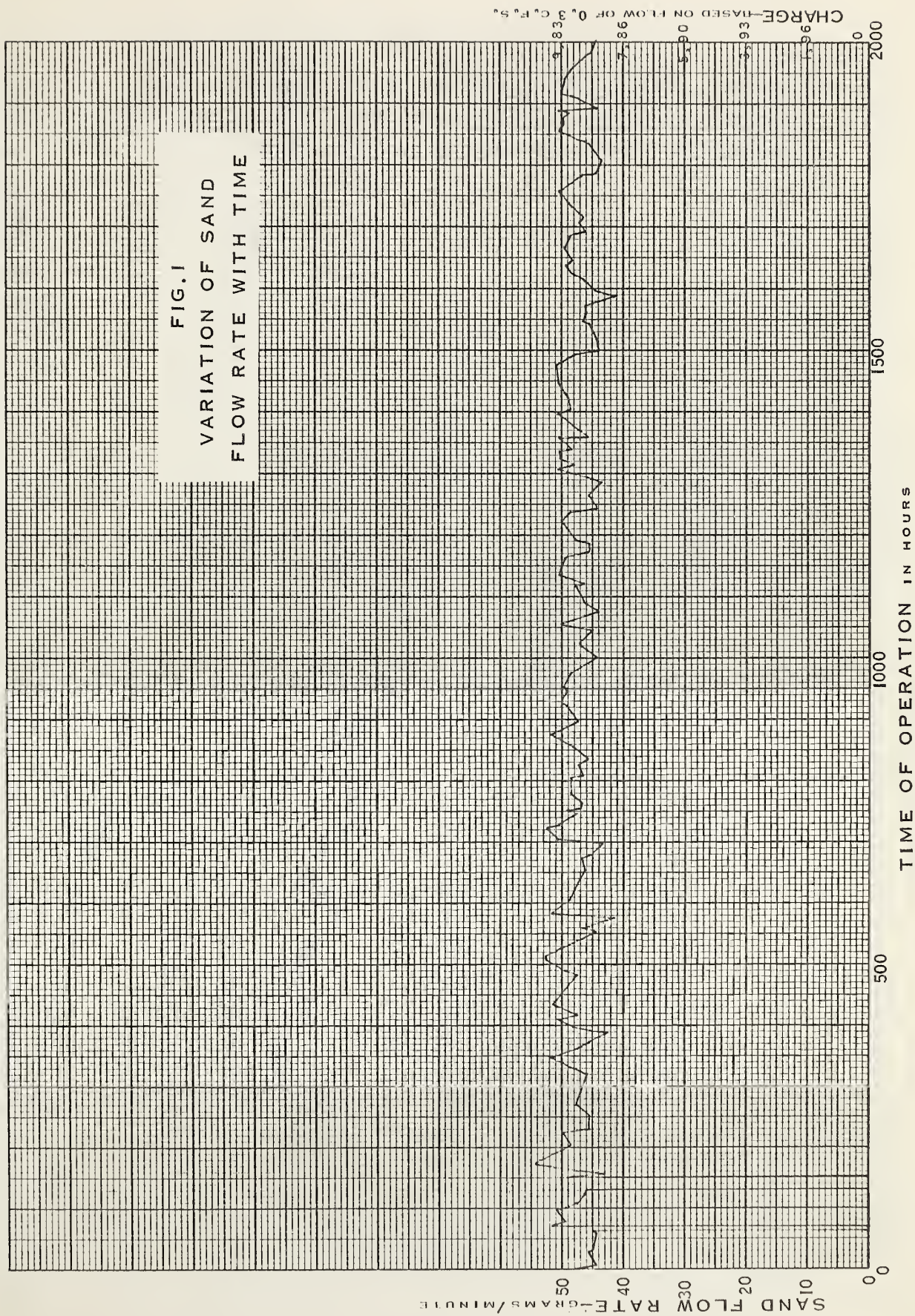


FIG. 2
BACKWATER EFFECTS OF 1/2 INCH PONDING
TIME = 970 HOURS

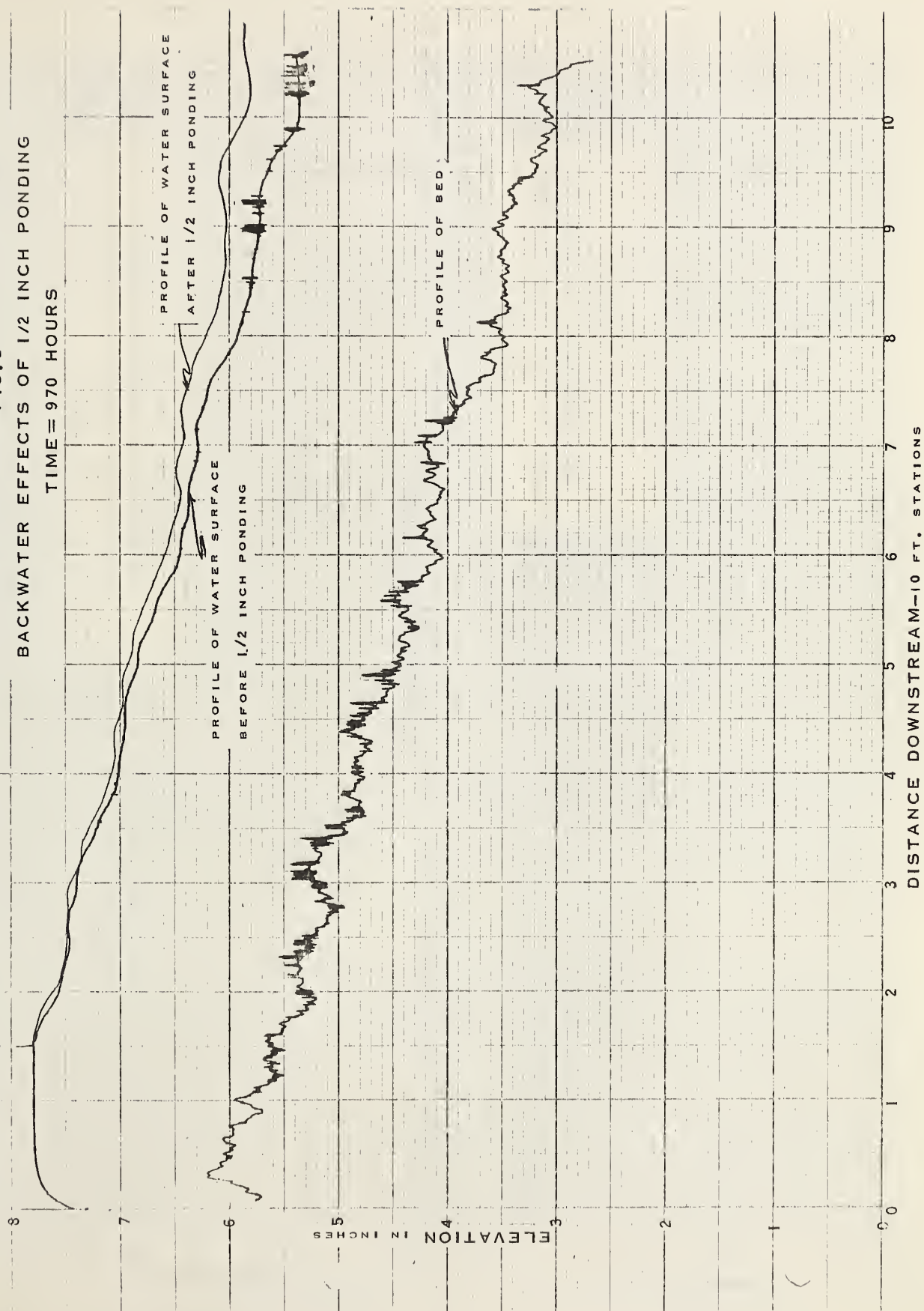


FIG. 4

TYPICAL GRAIN SIZE DISTRIBUTION
CURVE OF BED MATERIAL
AS FOUND BY SIEVE ANALYSIS

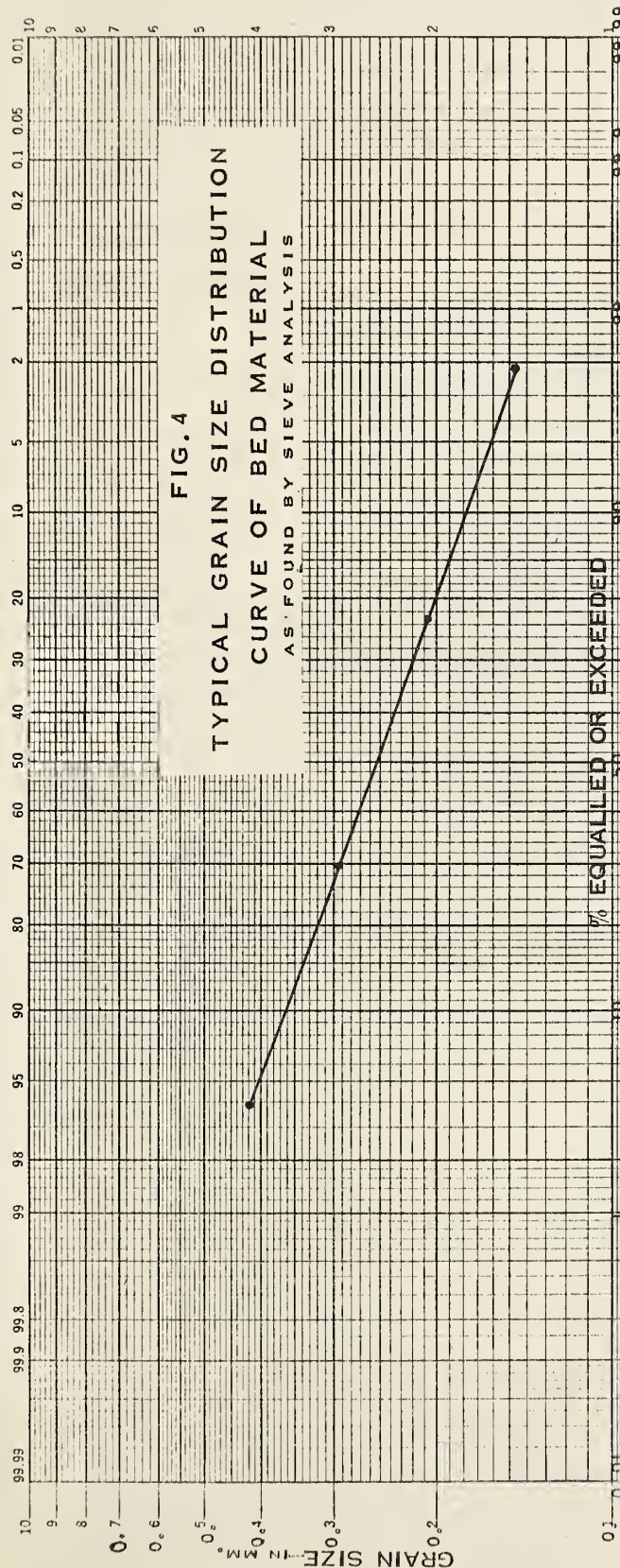
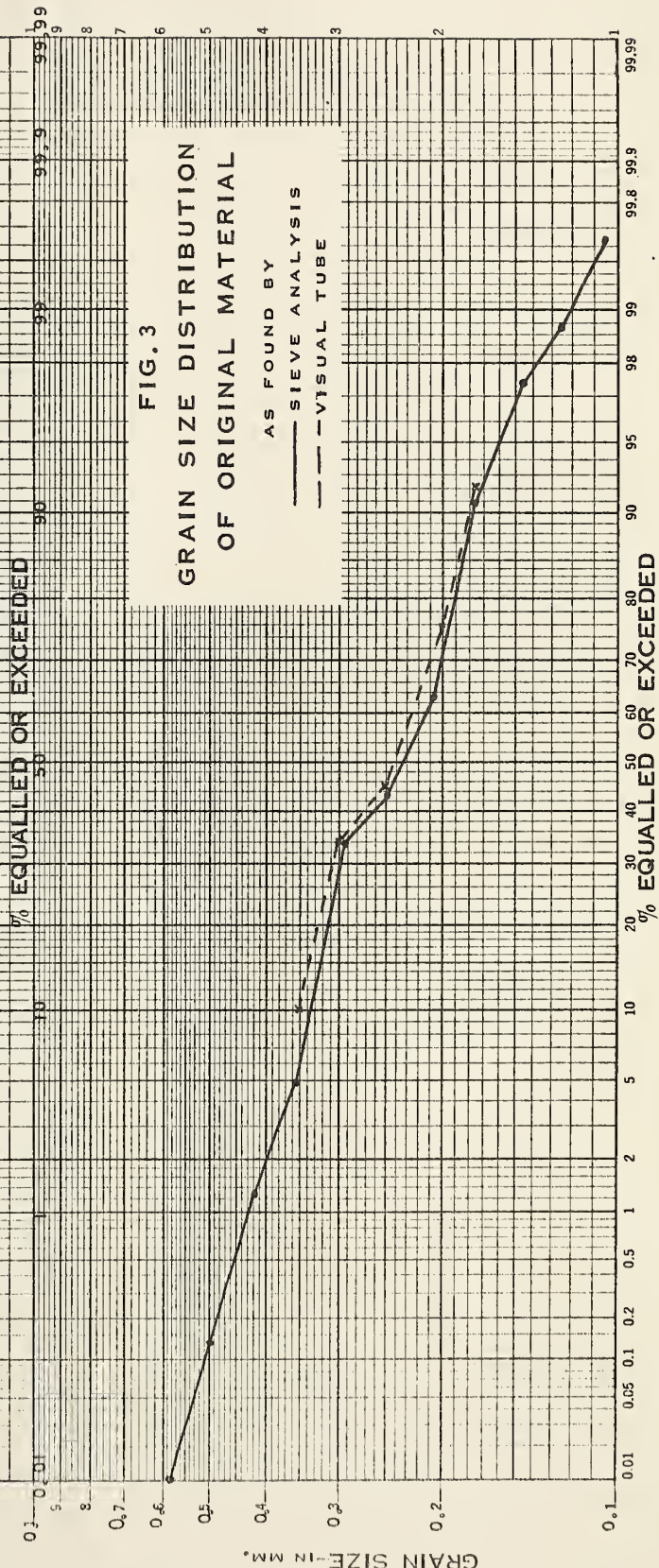


FIG. 3

GRAIN SIZE DISTRIBUTION
OF ORIGINAL MATERIAL

AS FOUND BY
— SIEVE ANALYSIS
- - - VISUAL TUBE



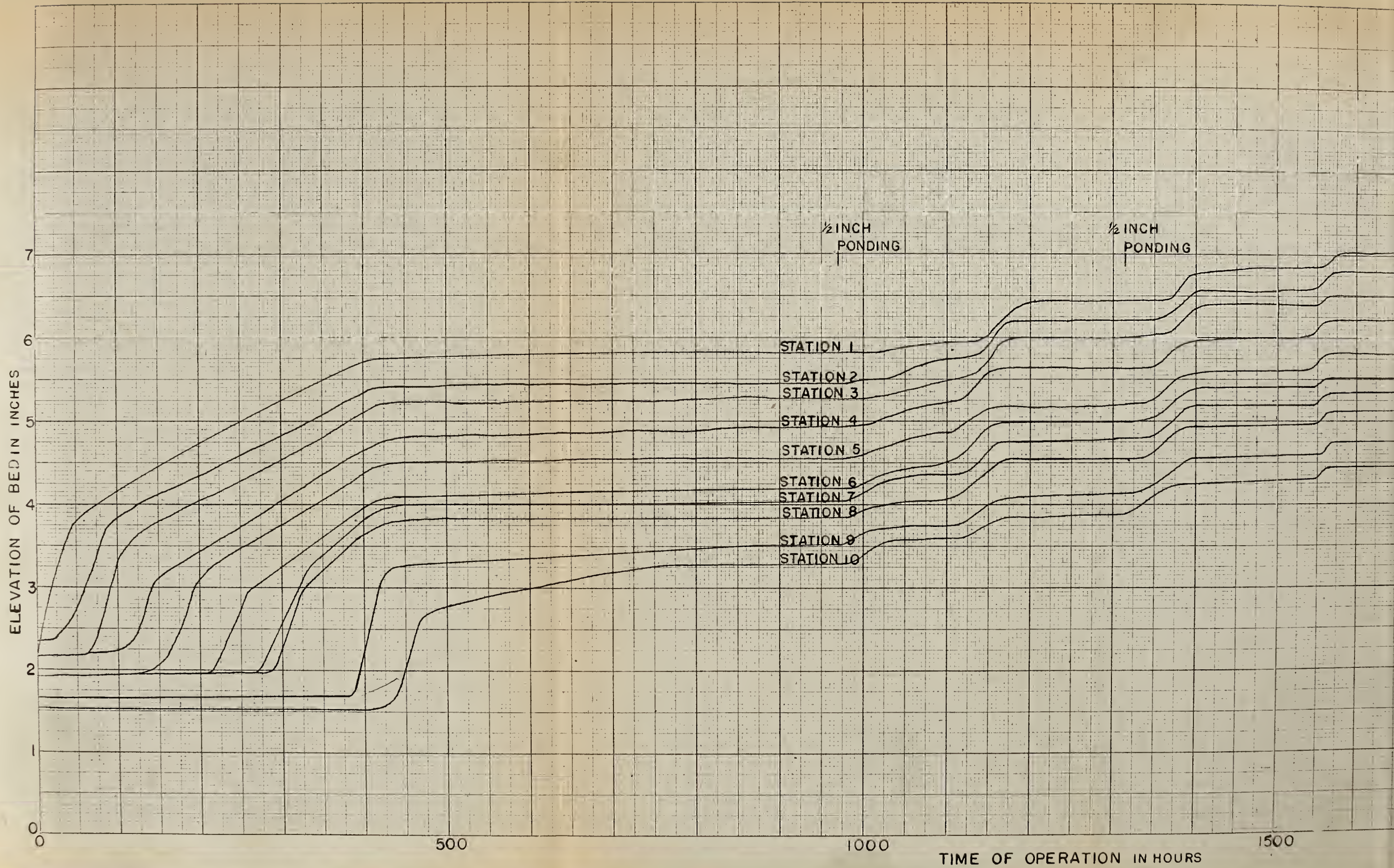
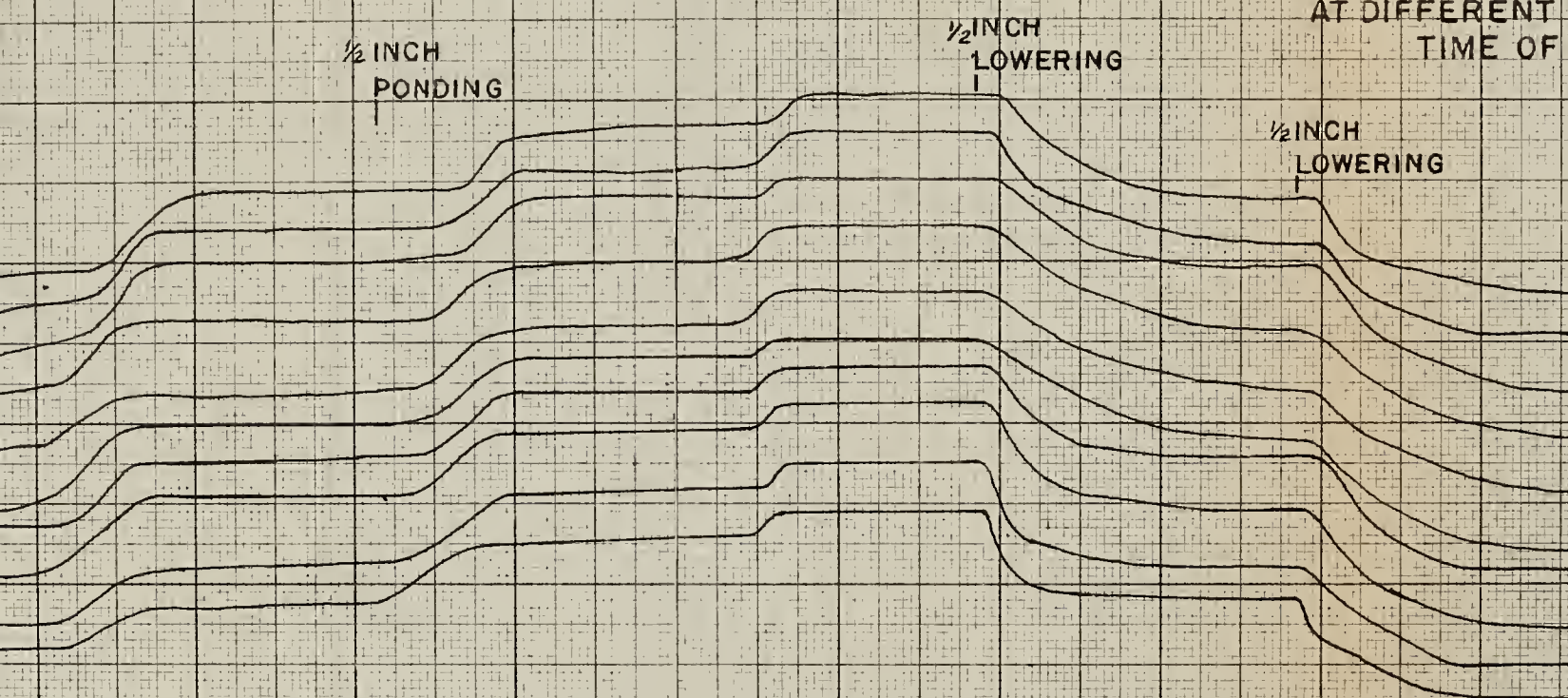


FIG. 5
VARIATION OF BED ELEVATION
AT DIFFERENT STATIONS WITH
TIME OF OPERATION



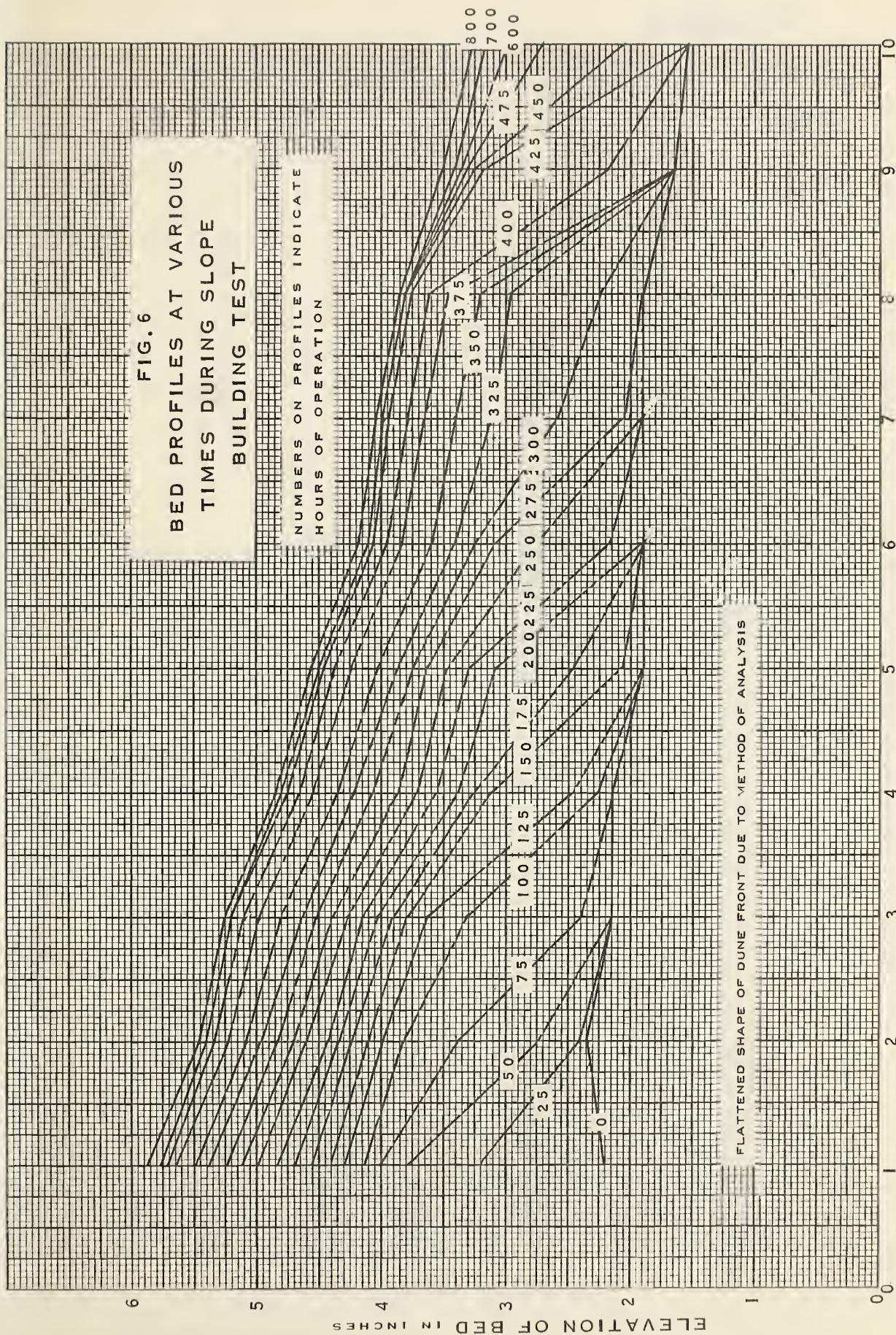
TIME OF OPERATION IN HOURS

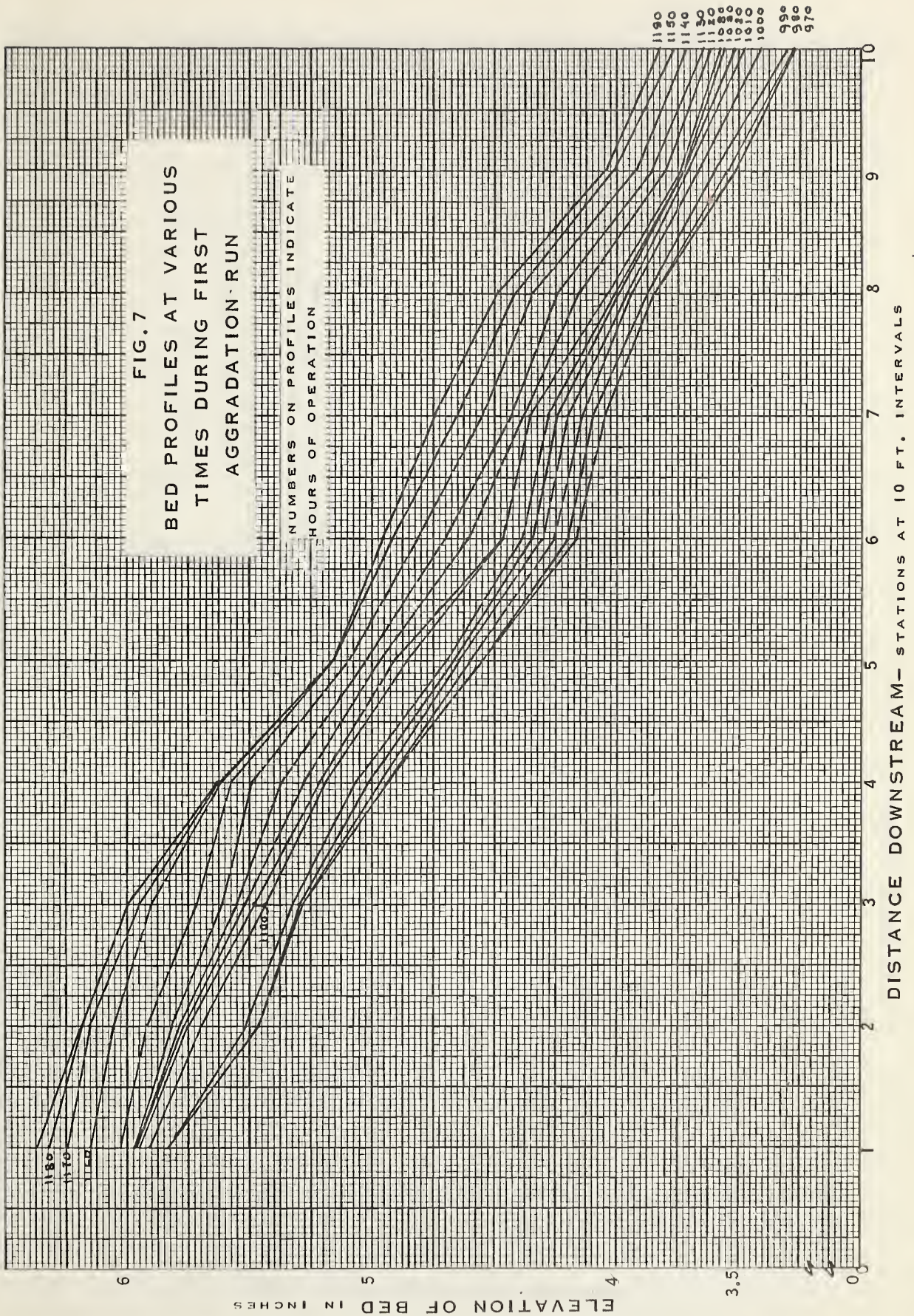
1500

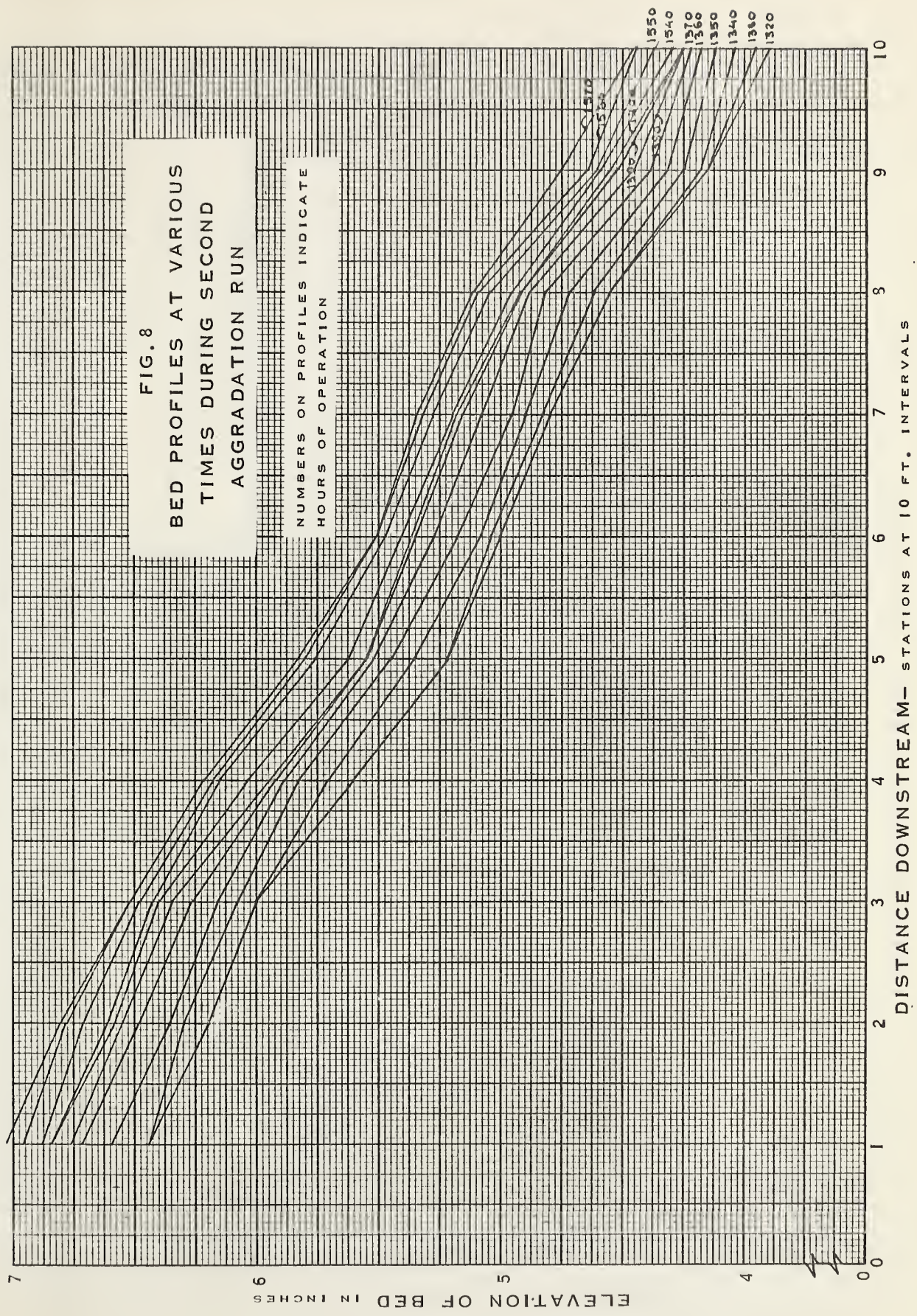
2000

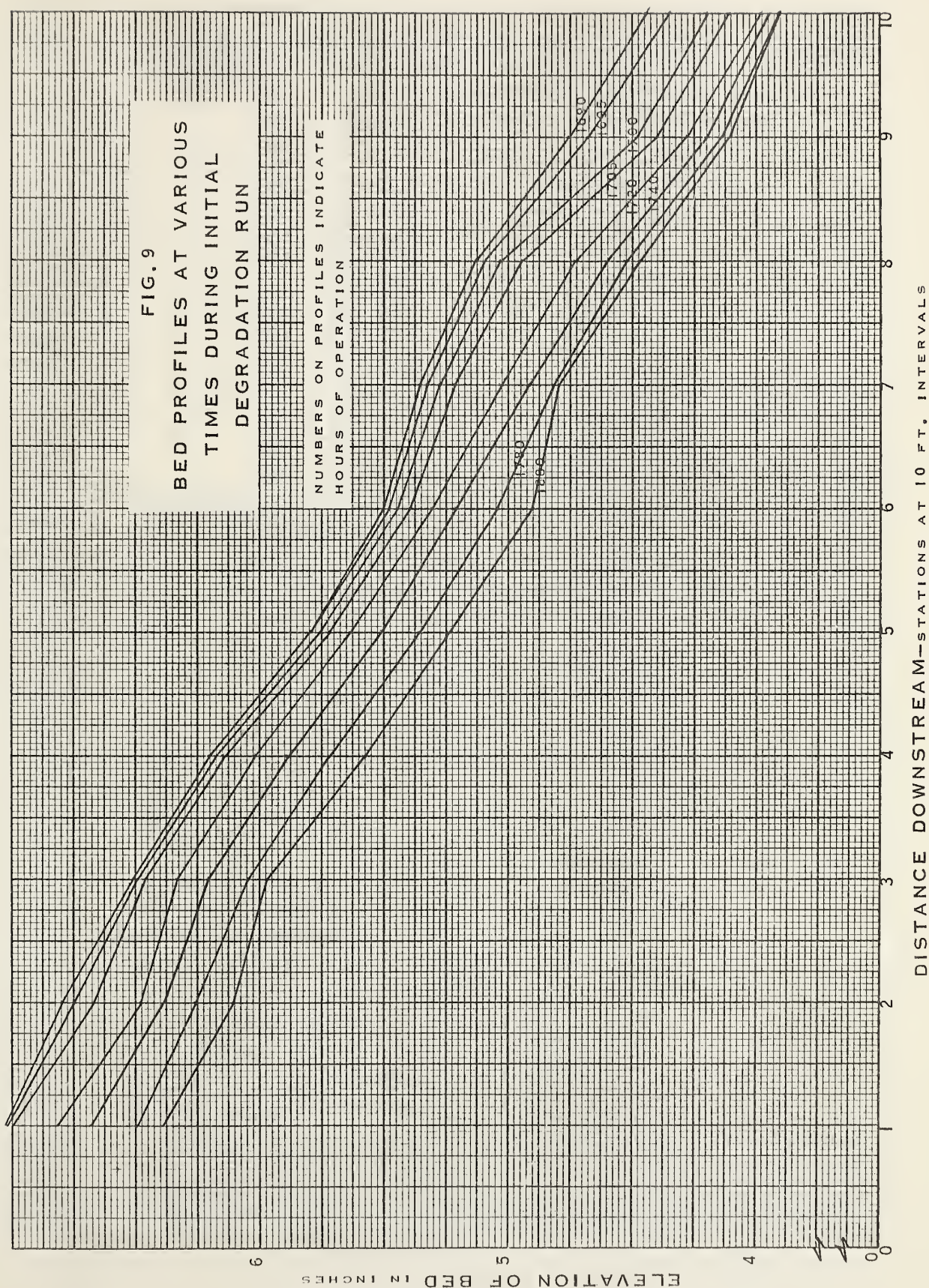
FIG. 6
BED PROFILES AT VARIOUS
TIMES DURING SLOPE
BUILDING TEST

NUMBERS ON PROFILES INDICATE
HOURS OF OPERATION









ELEVATION OF WATER SURFACE IN INCHES

8

7

6

5

4

3

2

1

0

0

500

STATION 1

STATION 2

STATION 3

STATION 4

STATION 5

STATION 6

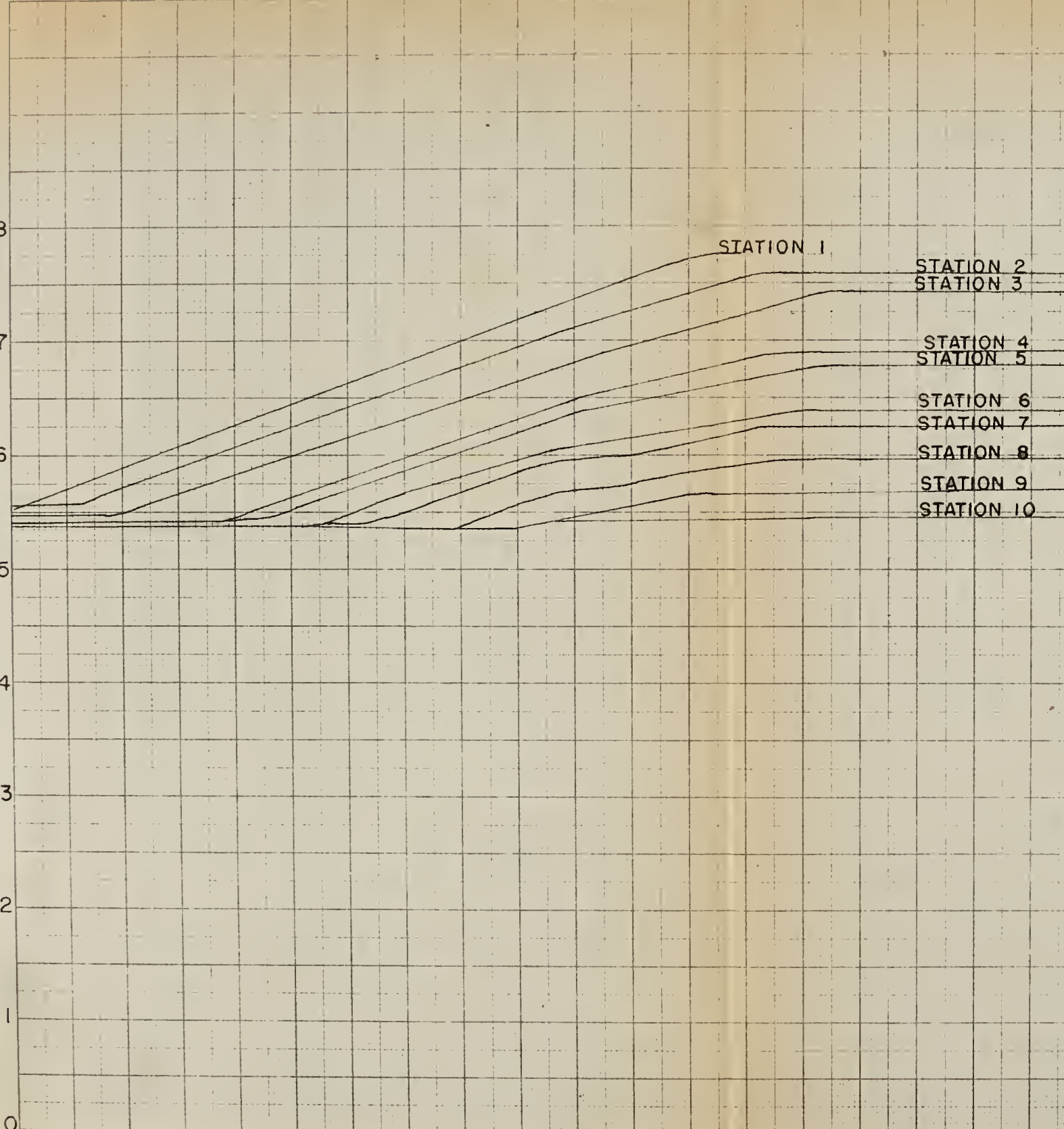
STATION 7

STATION 8

STATION 9

STATION 10

TIME



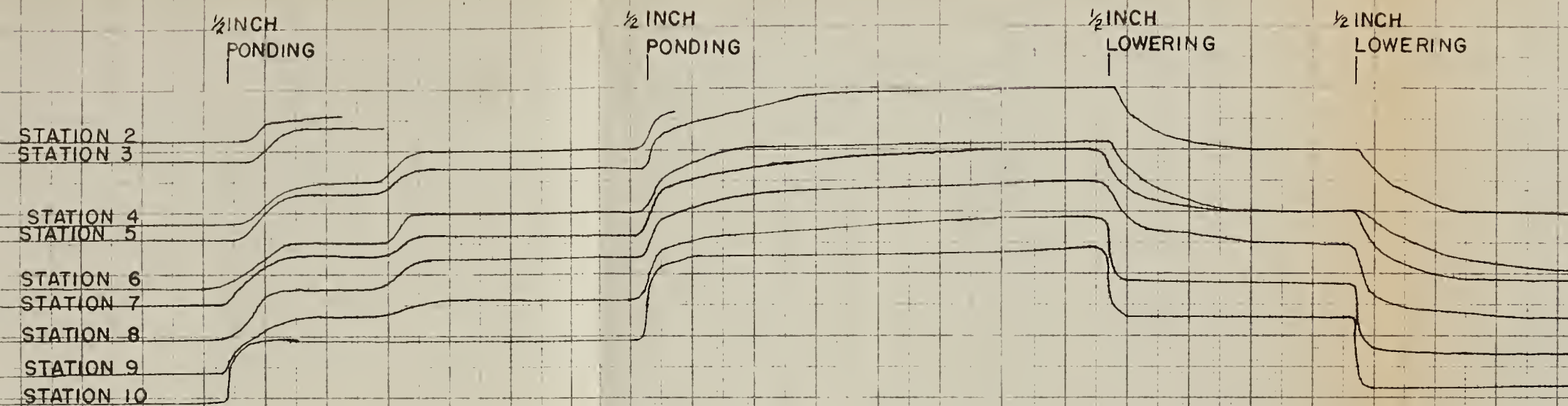


FIG. II
VARIATION OF WATER SURFACE
ELEVATION AT VARIOUS STATIONS
DURING TIME OF OPERATION

FIG. 12
WATER SURFACE PROFILES AT
VARIOUS TIMES DURING SLOPE
BUILDING TEST

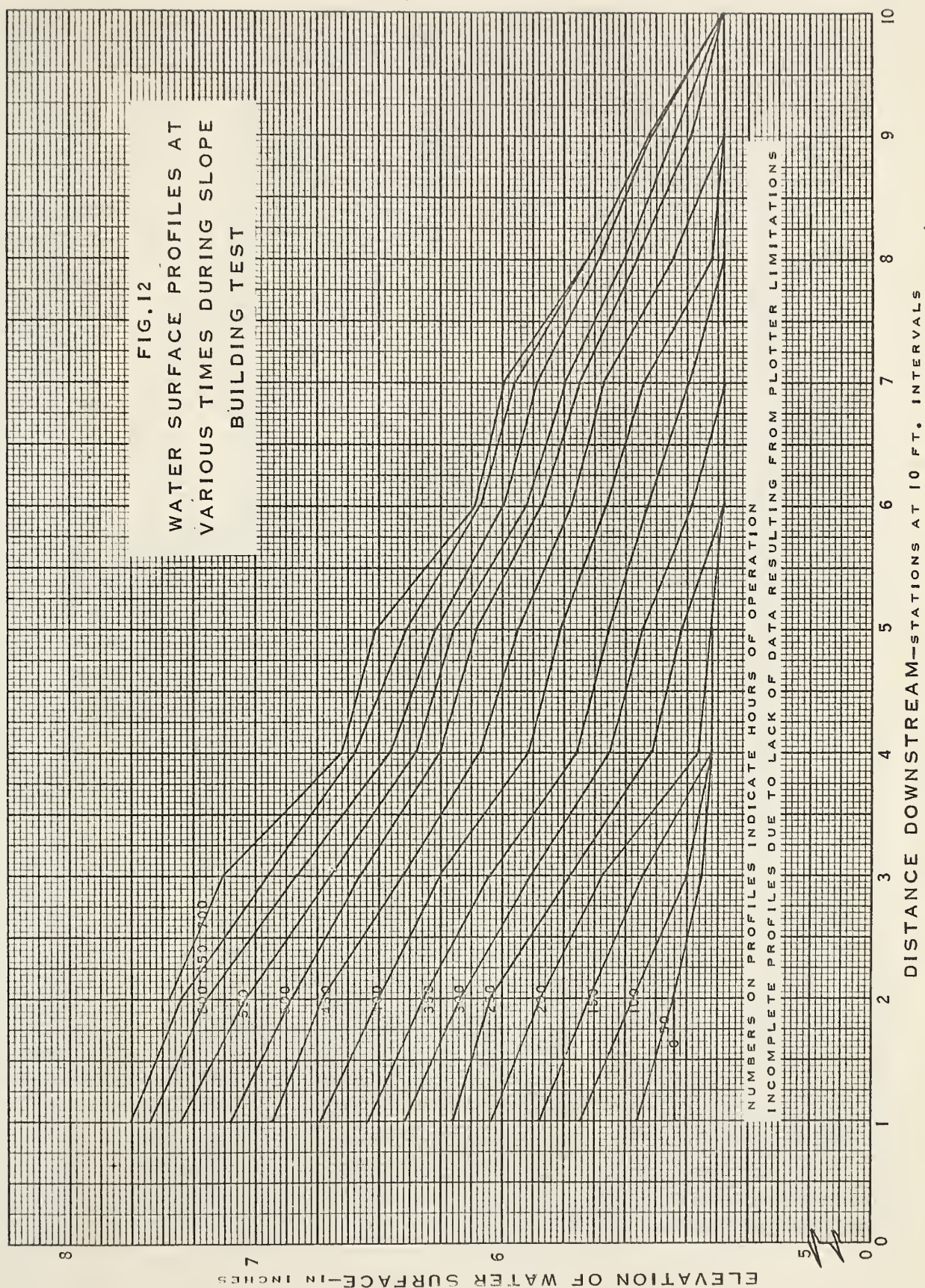


FIG. 13
WATER SURFACE PROFILES AT
VARIOUS TIMES DURING FIRST
AGGRADATION RUN

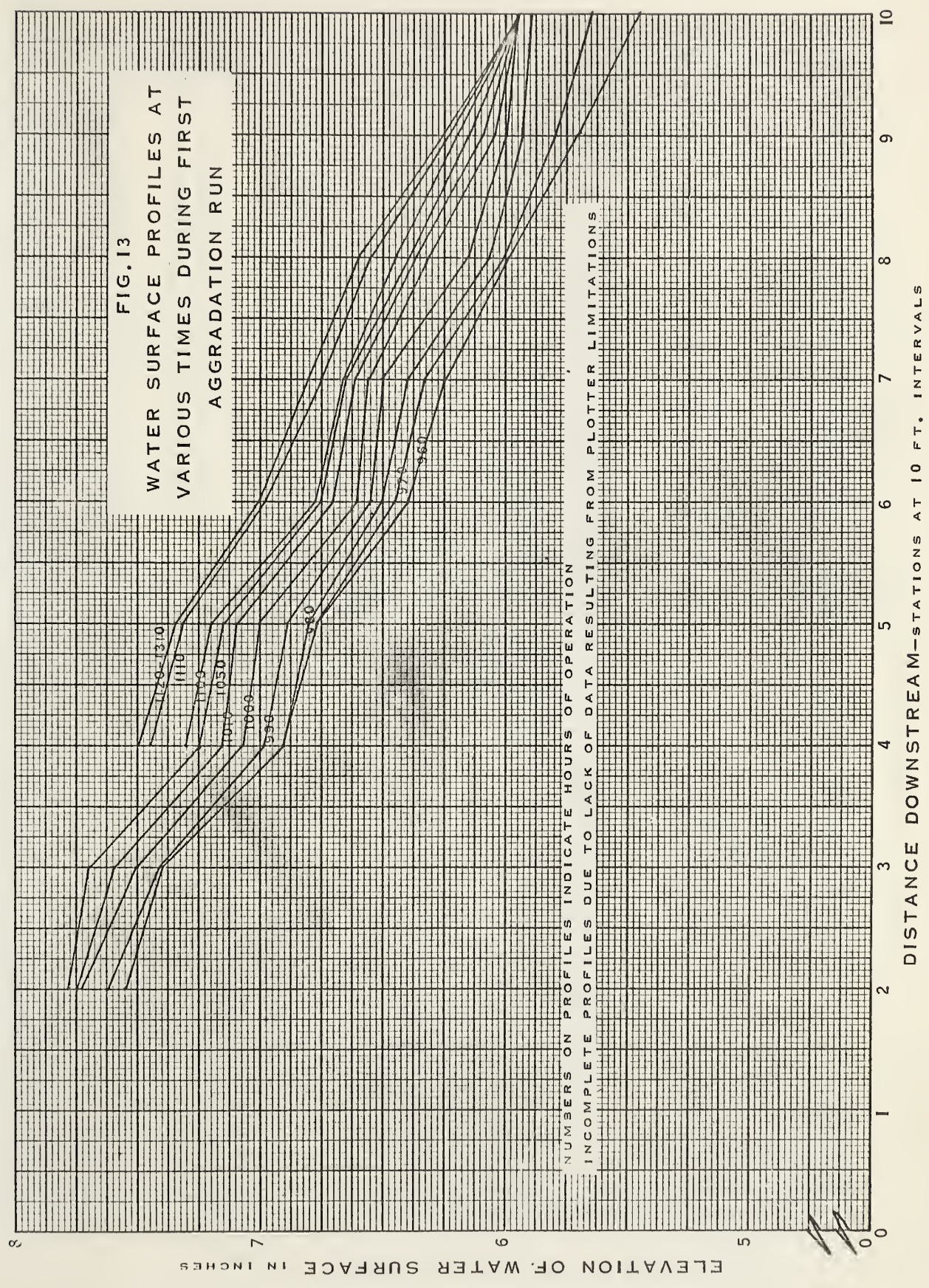


FIG. 14
WATER SURFACE PROFILES AT
VARIOUS TIMES DURING SECOND
AGGRADATION RUN

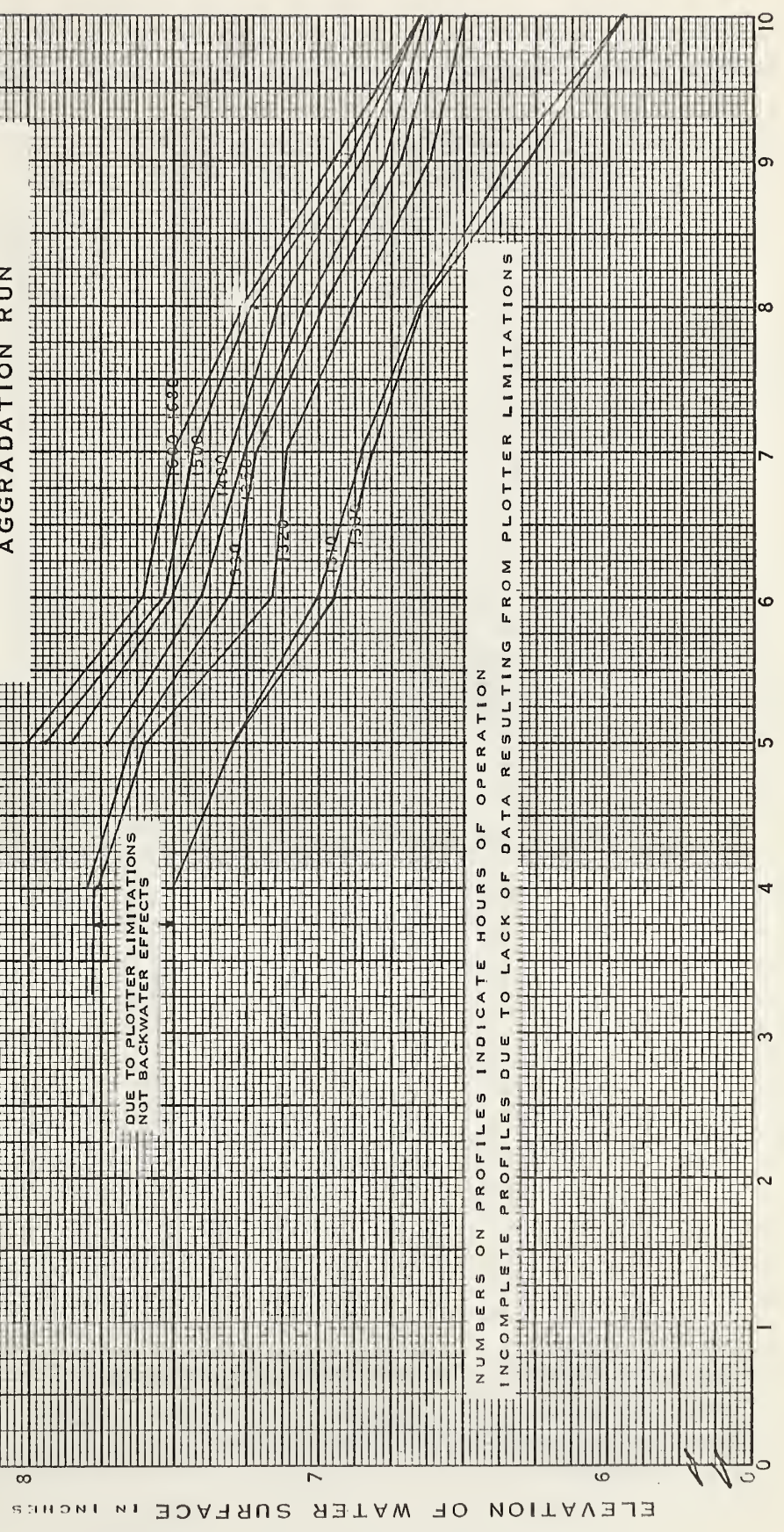


FIG. 15

WATER SURFACE PROFILES AT
VARIOUS TIMES DURING FIRST
DEGRADATION RUN

ELEVATION OF WATER SURFACE IN INCHES

NUMBERS ON PROFILES INDICATE HOURS OF OPERATION
INCOMPLETE PROFILES DUE TO LACK OF DATA RESULTING FROM PLOTTER LIMITATIONS

DISTANCE DOWNSTREAM—STATIONS AT 10 FT. INTERVALS

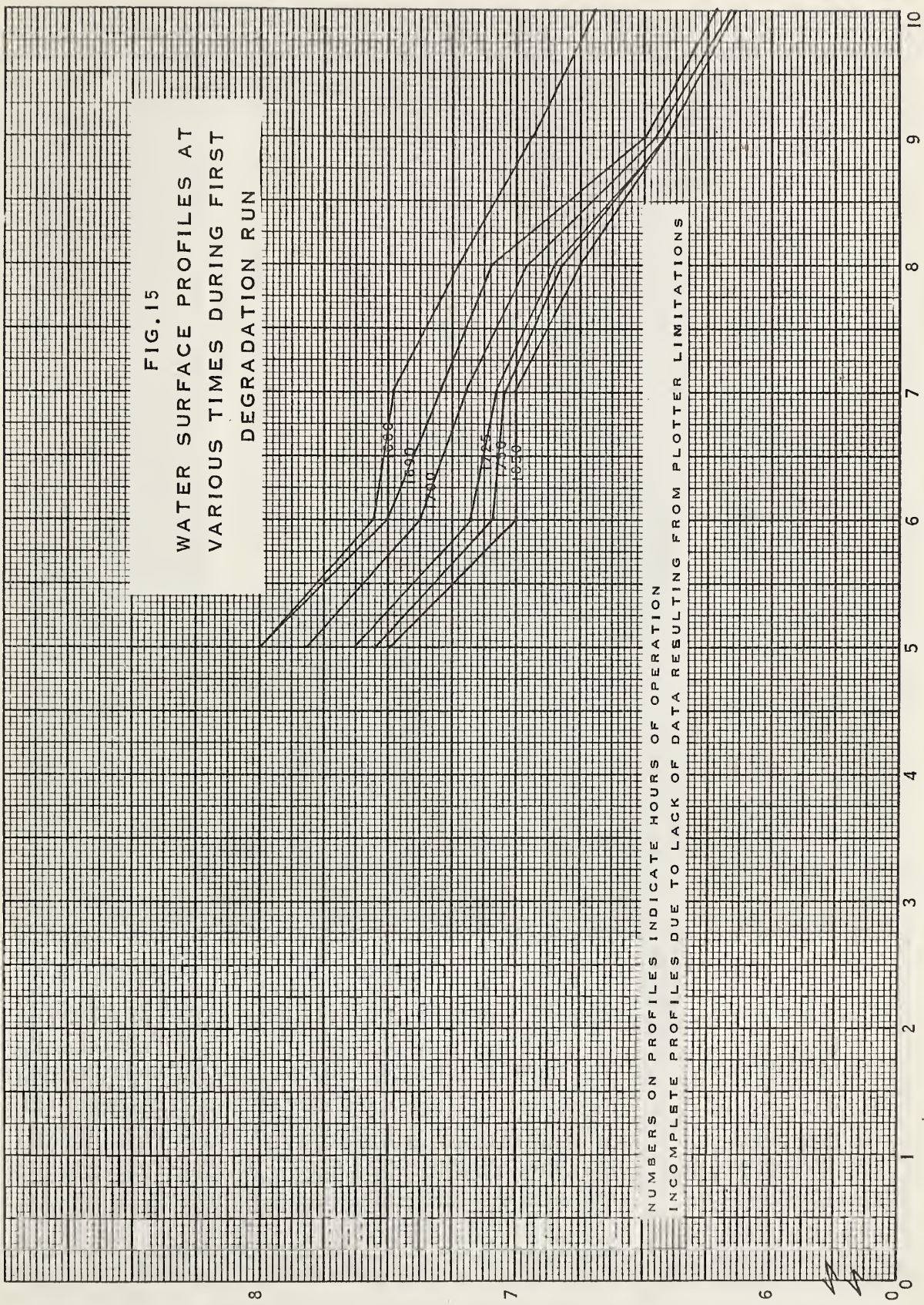
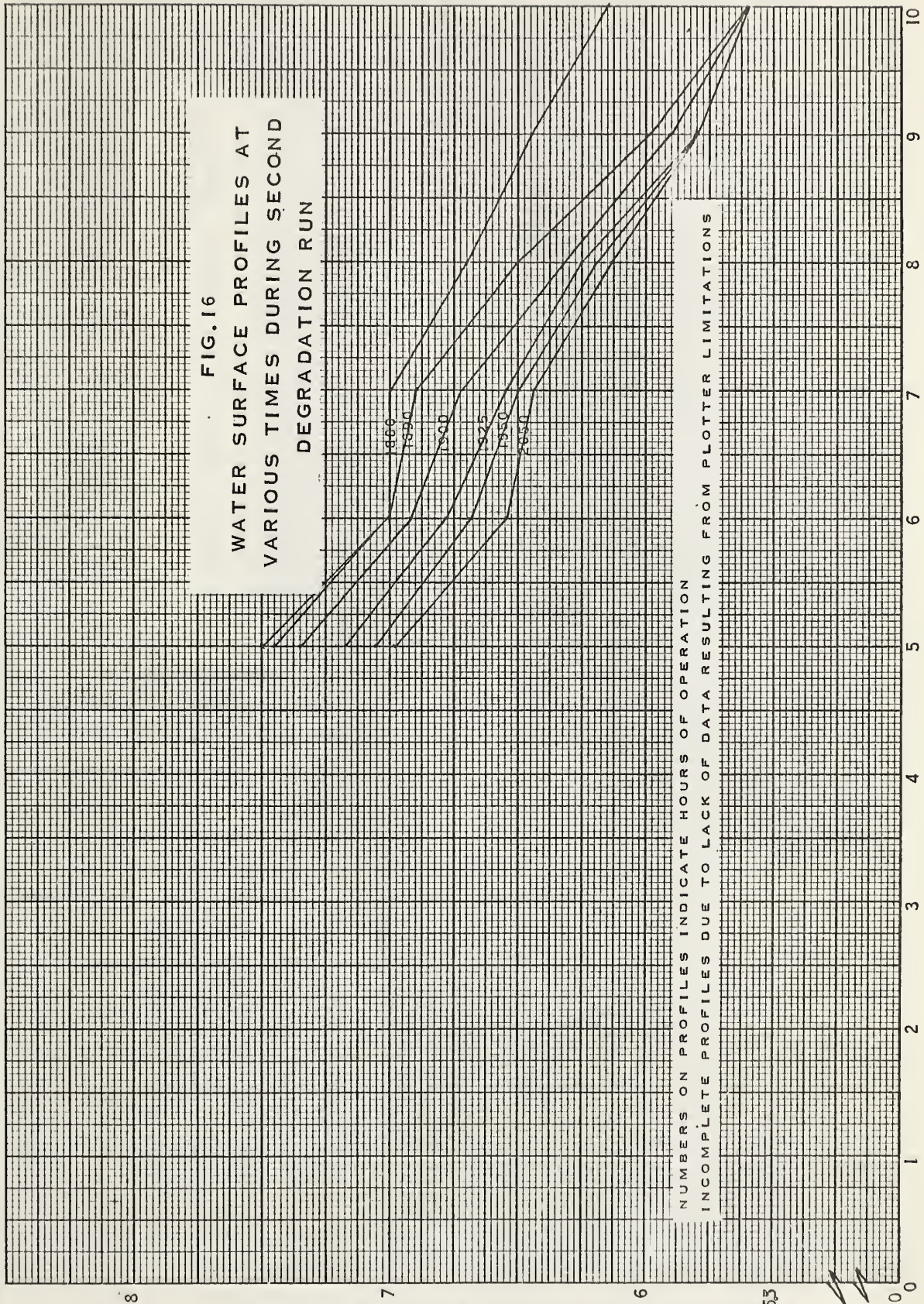


FIG. 16
WATER SURFACE PROFILES AT
VARIOUS TIMES DURING SECOND
DEGRADATION RUN

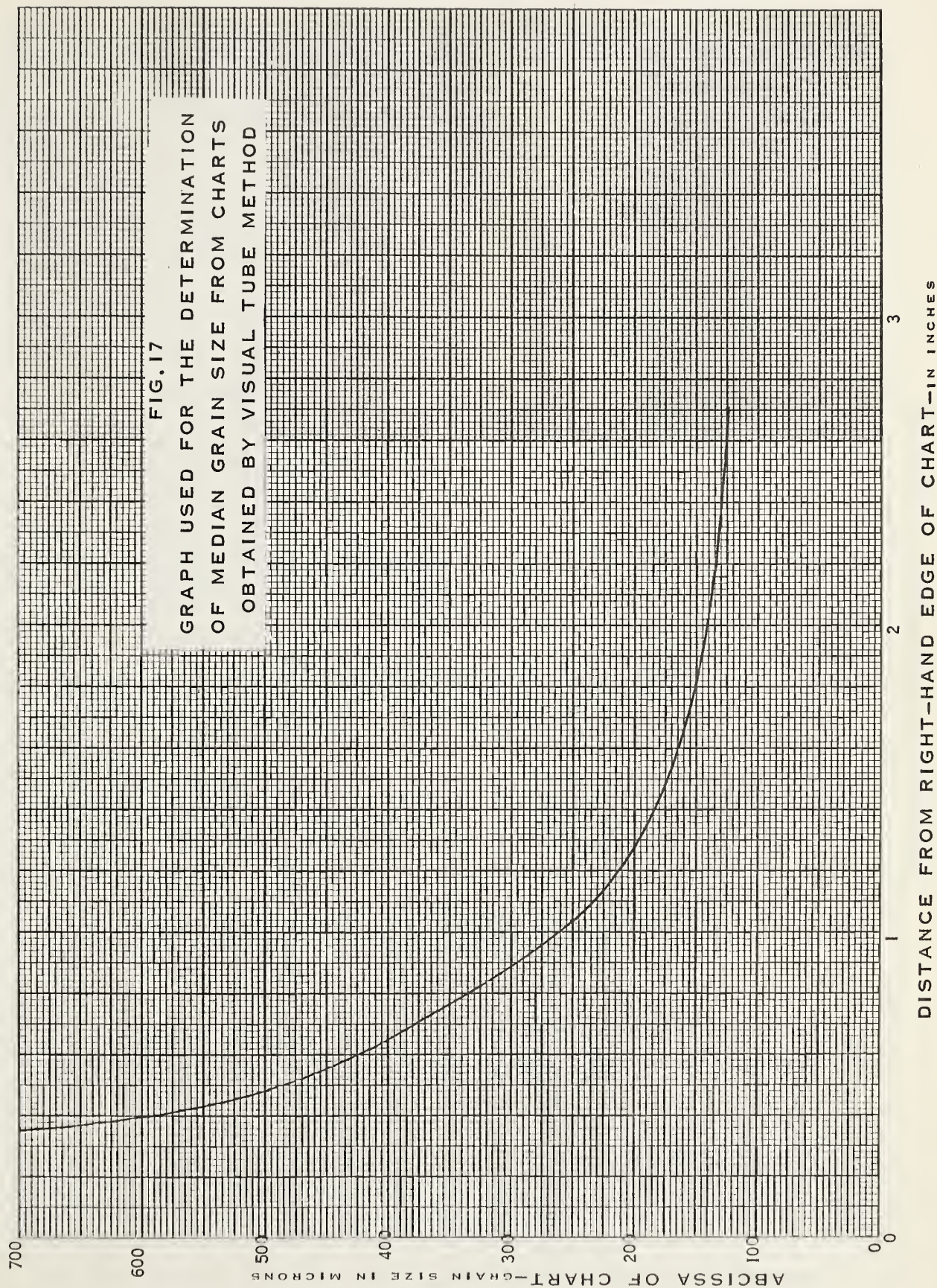
ELEVATION OF WATER SURFACE IN INCHES

NUMBERS ON PROFILES INDICATE HOURS OF OPERATION
INCOMPLETE PROFILES DUE TO LACK OF DATA RESULTING FROM PLOTTER LIMITATIONS

DISTANCE DOWNSTREAM-STATIONS AT 10 FT. INTERVALS







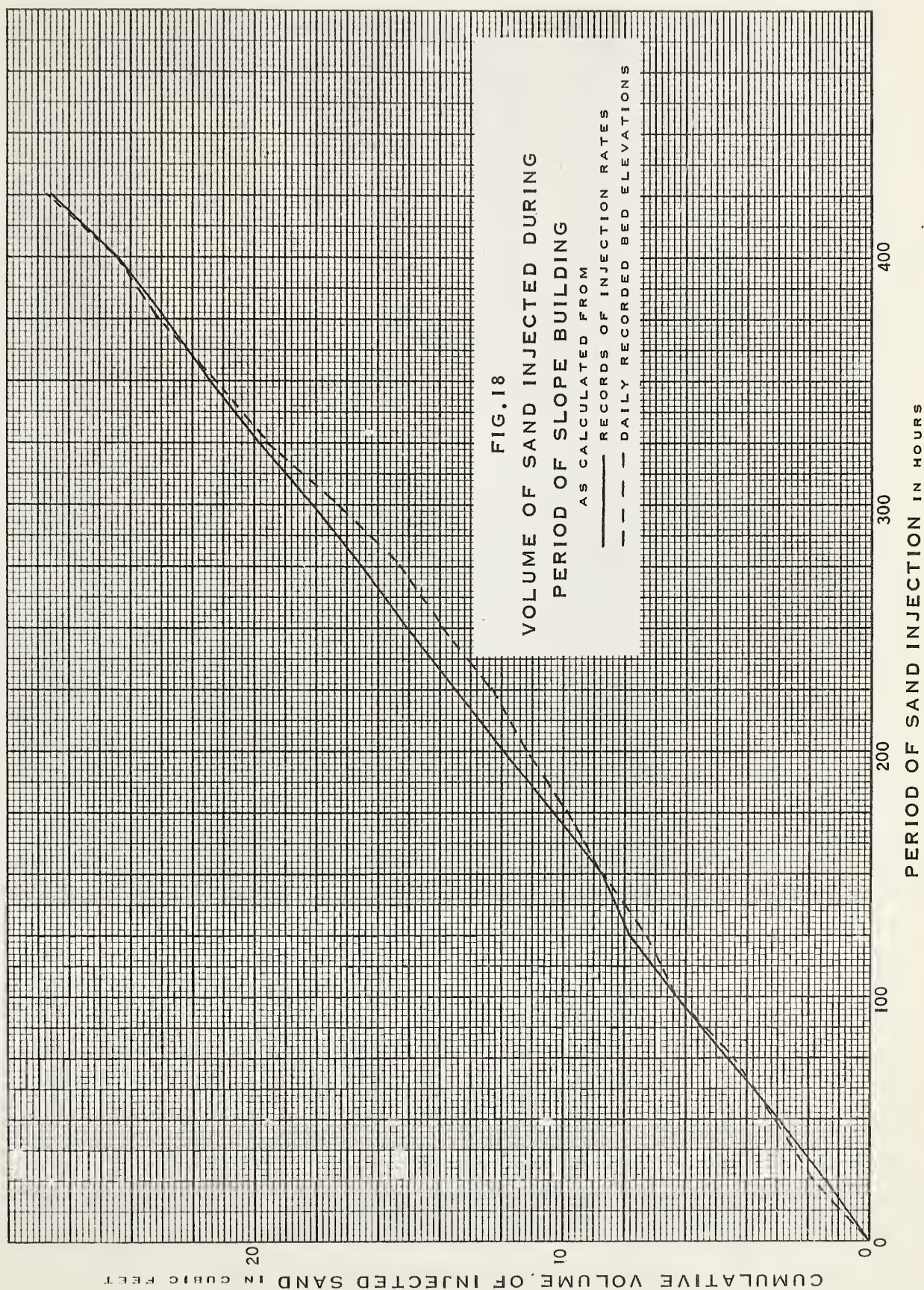
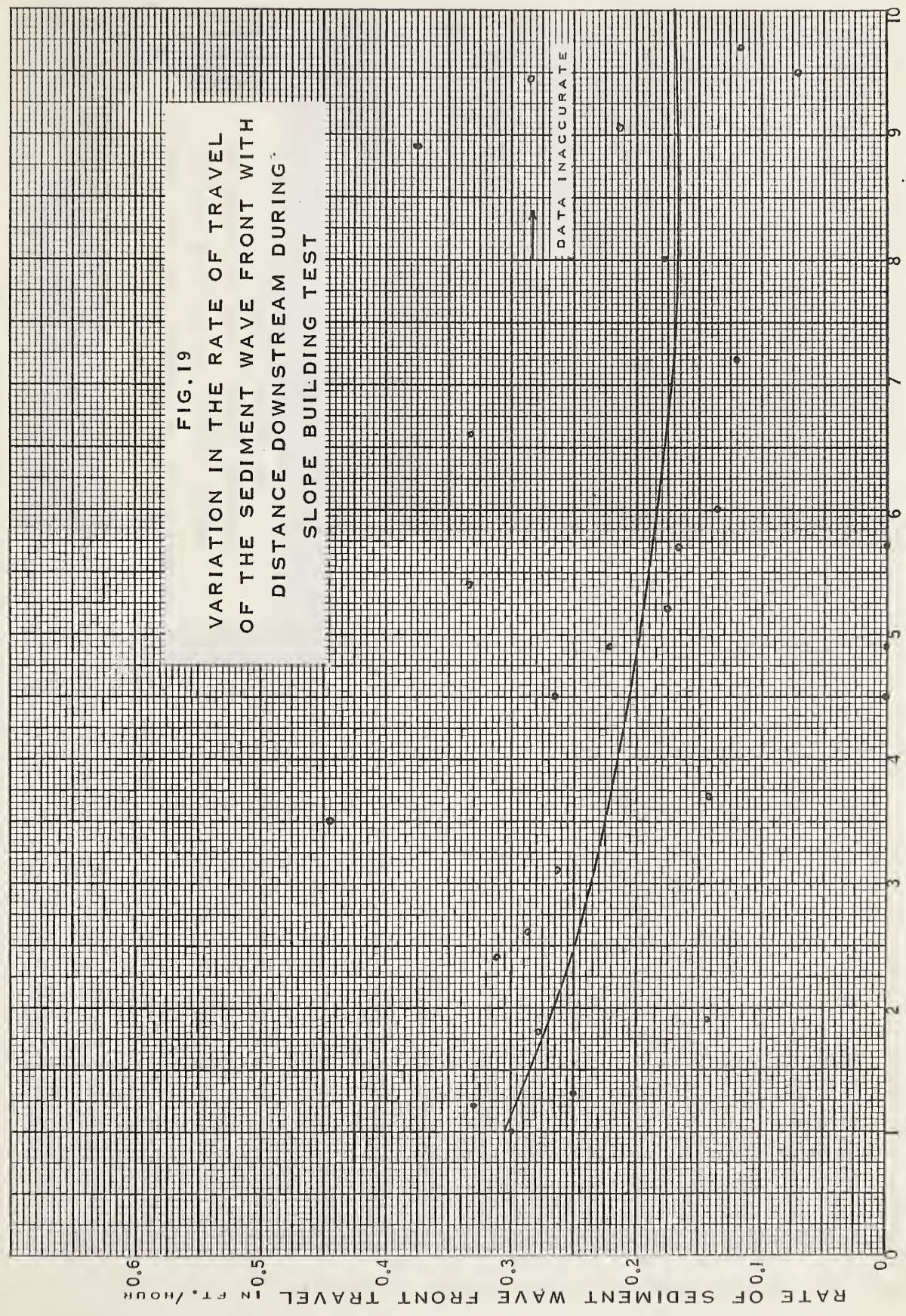


FIG. 19
VARIATION IN THE RATE OF TRAVEL
OF THE SEDIMENT WAVE FRONT WITH
DISTANCE DOWNSTREAM DURING
SLOPE BUILDING TEST



DISTANCE DOWNSTREAM-STATIONS AT 10 FT. INTERVALS

FIG. 20
 VARIATION IN HEIGHT OF SEDIMENT
 WAVE FRONT WITH DISTANCE
 DOWNSTREAM DURING PERIOD
 OF SLOPE BUILDING

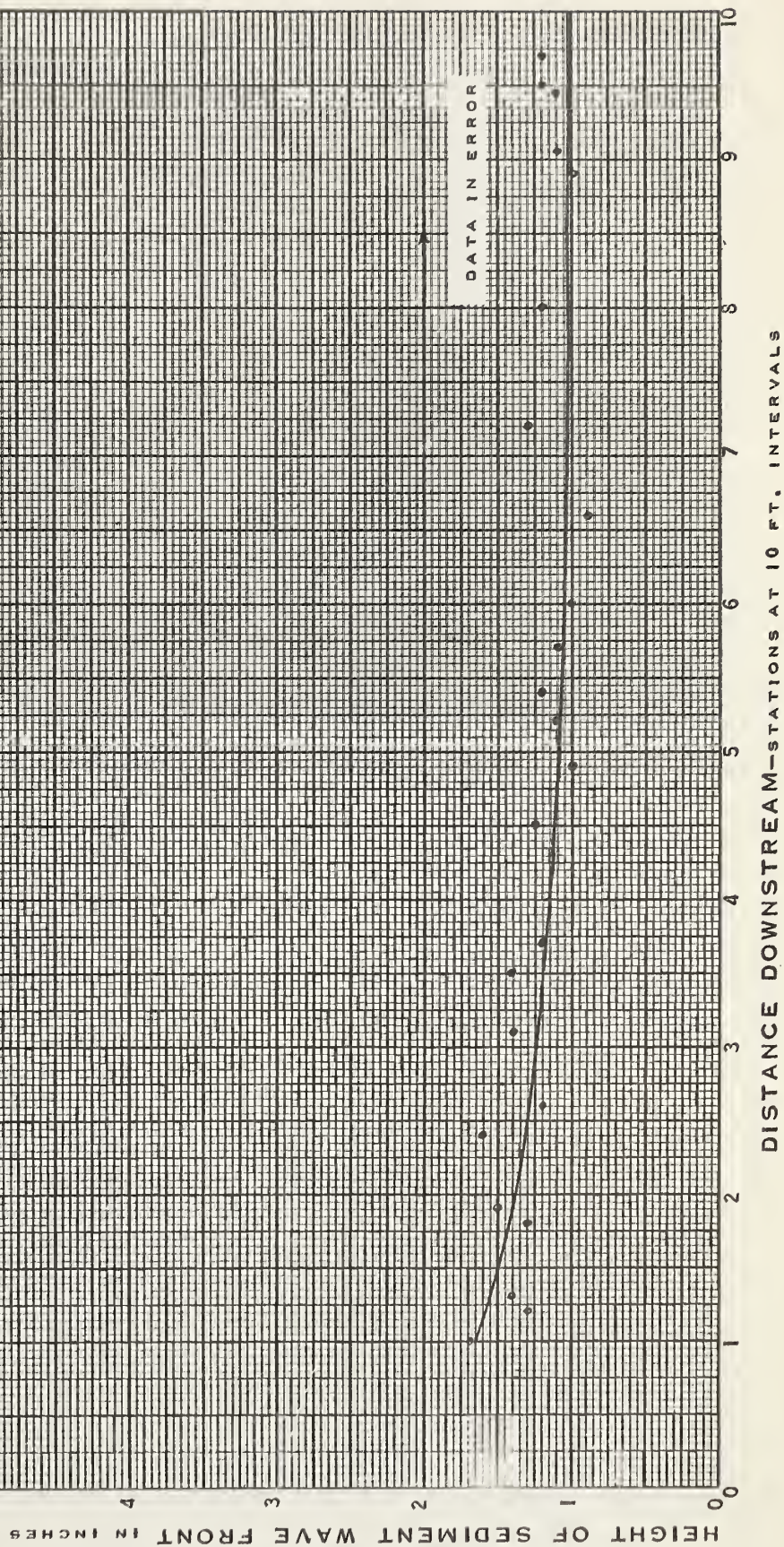


FIG. 21
VARIATION OF AVERAGE MEDIAN
GRAIN SIZE WITH POSITION IN
FLUME

AVERAGE MEDIAN GRAIN SIZE IN MM.

DISTANCE DOWNSTREAM—STATIONS AT 10 FT. INTERVALS

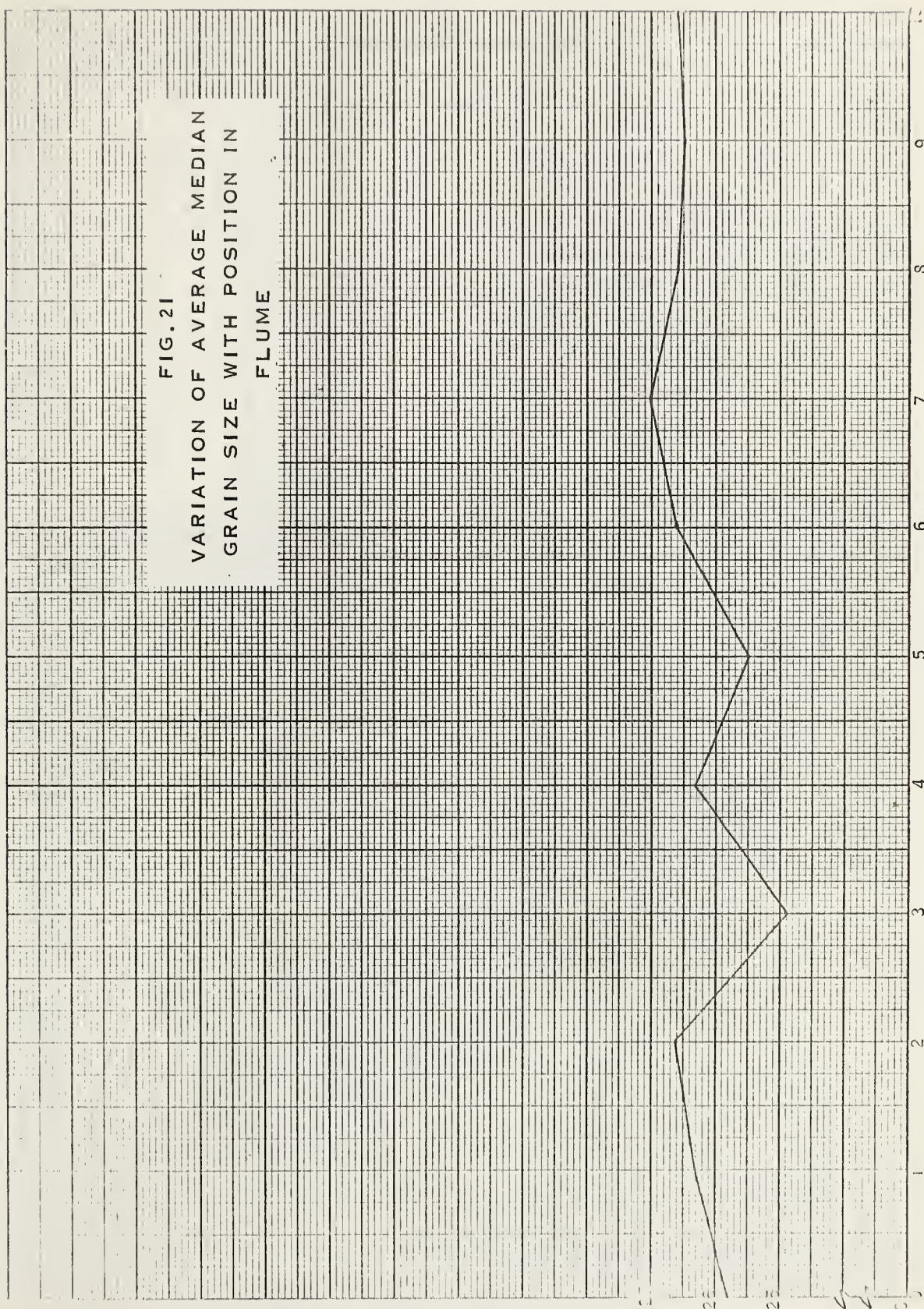


FIG. 22A
 VARIATION OF MEDIAN
 GRAIN SIZE WITH TIME
 FOR VARIOUS STATIONS
 AT TEN FT. SPACING



FIG. 22B
 VARIATION OF MEDIAN
 GRAIN SIZE WITH TIME
 FOR VARIOUS STATIONS
 AT TEN FT. SPACING

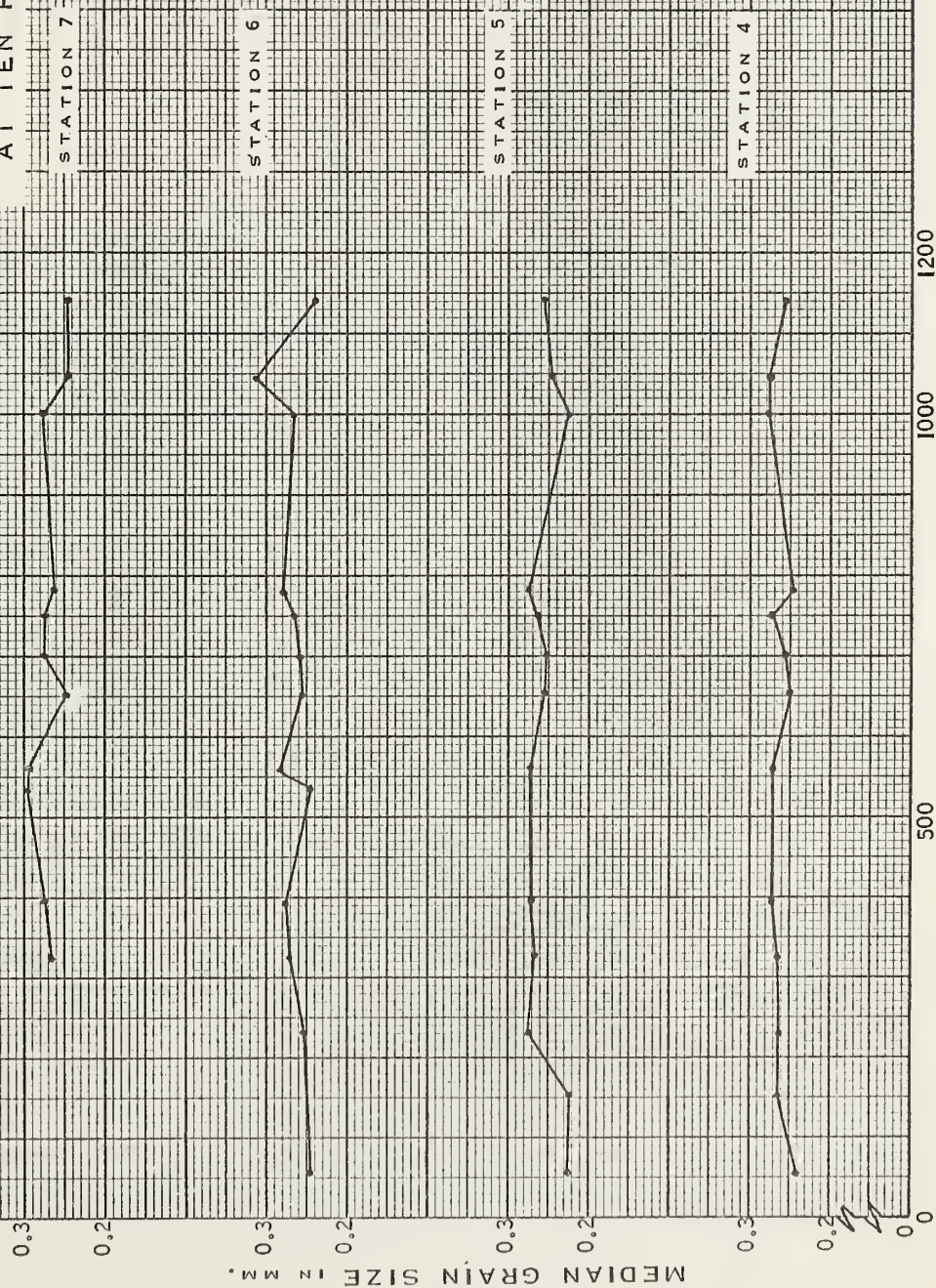


FIG. 22C
VARIATION OF MEDIAN
GRAIN SIZE WITH TIME
FOR VARIOUS STATIONS
AT TEN FT. SPACING

STATION 10

STATION 9

STATION 8

MEDIAN GRAIN SIZE IN MM.

500 1000 1200
TIME OF OPERATION IN HOURS

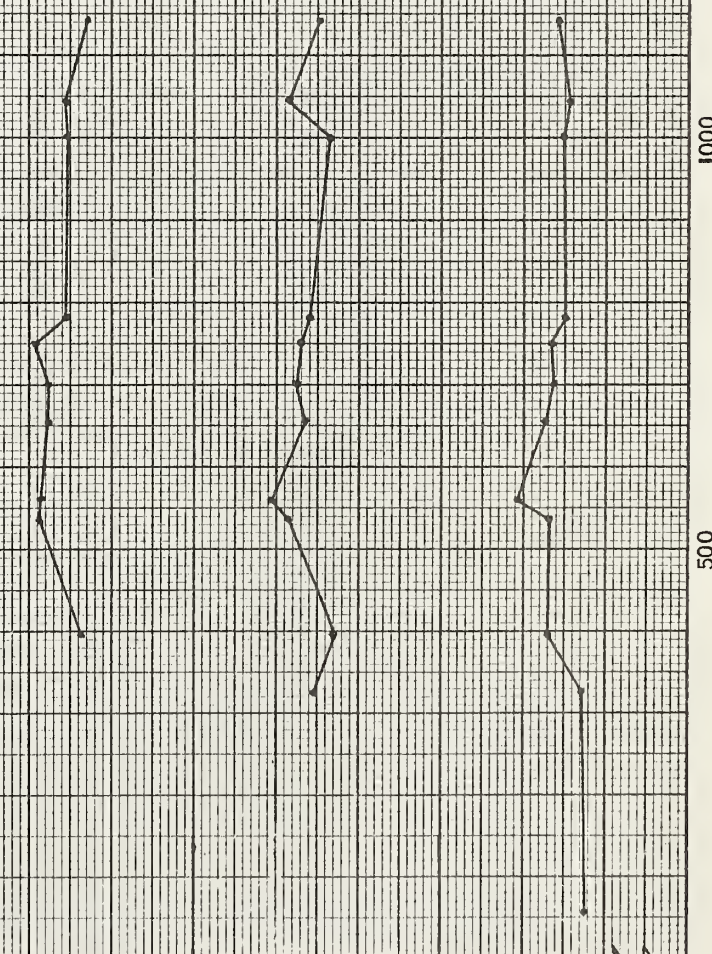
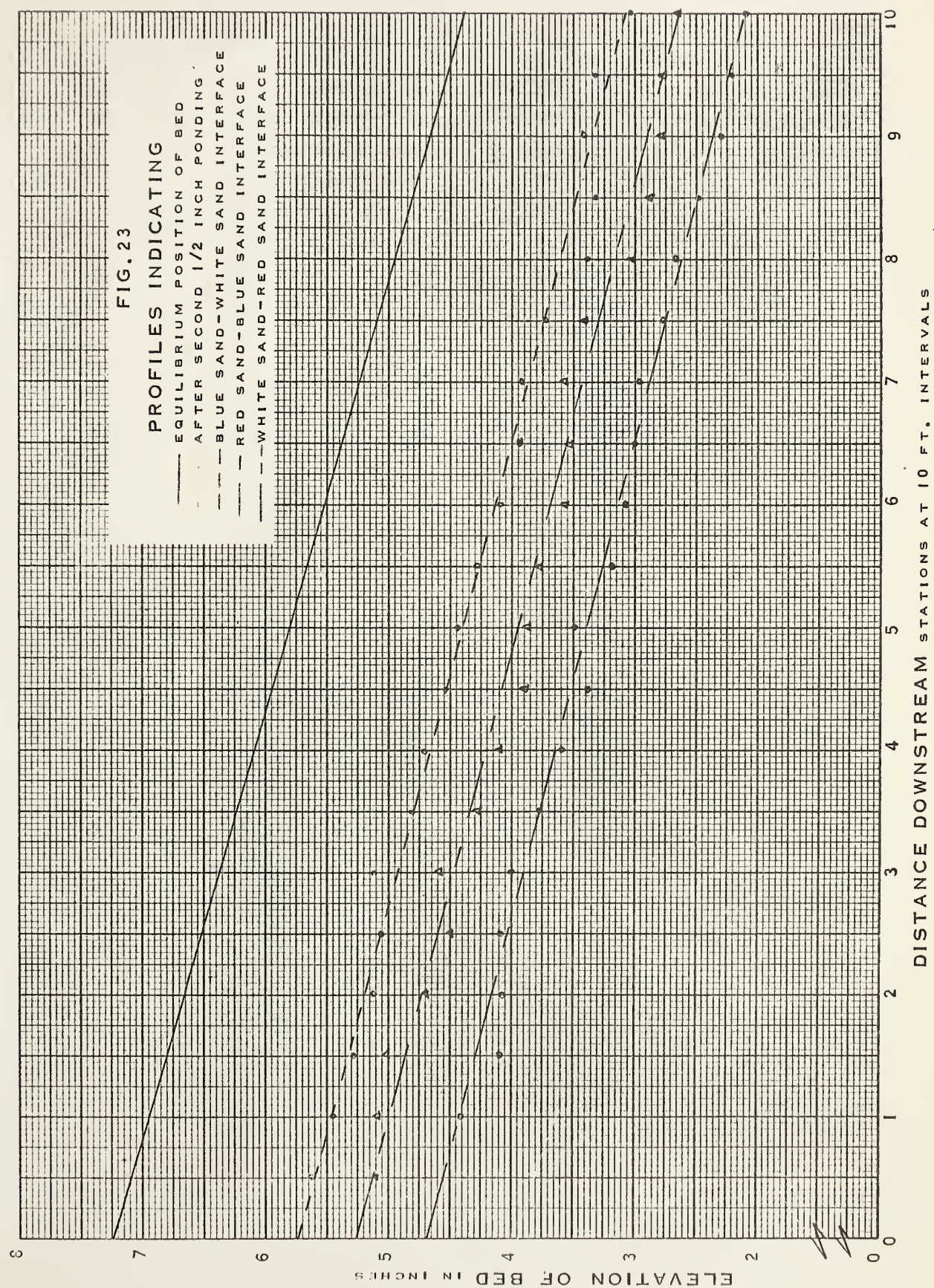


FIG. 23

PROFILES INDICATING

- EQUILIBRIUM POSITION OF BED
- - - AFTER SECOND 1/2 INCH PONDING
- - - BLUE SAND-WHITE SAND INTERFACE
- - - RED SAND-BLUE SAND INTERFACE
- - - WHITE SAND-RED SAND INTERFACE



APPENDIX C

PHOTOGRAPHS

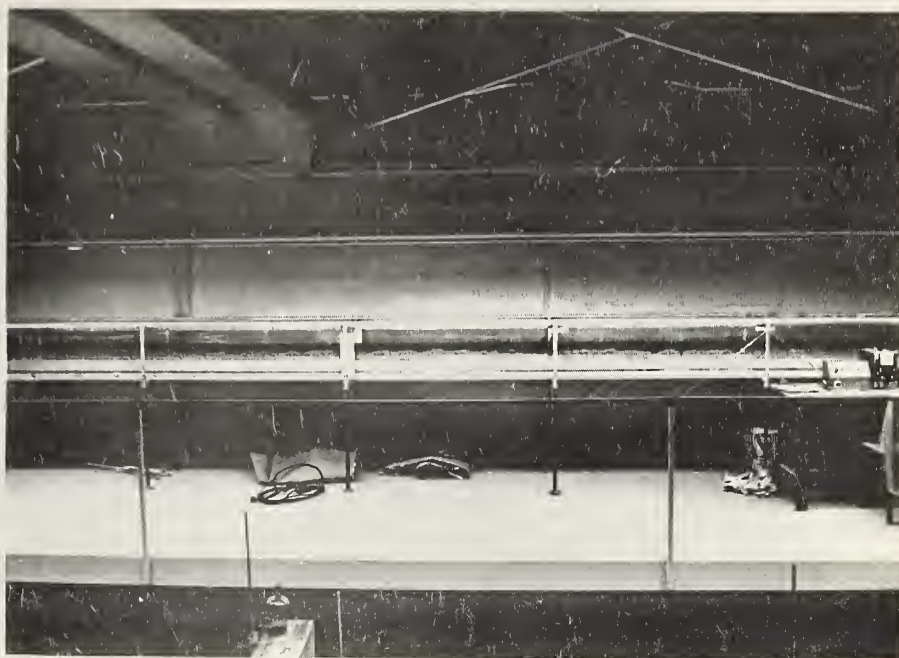


PLATE 1. VIEW OF MIDPORTION OF FLUME



PLATE 2. VIEW OF THE DOWNSTREAM END
OF THE FLUME

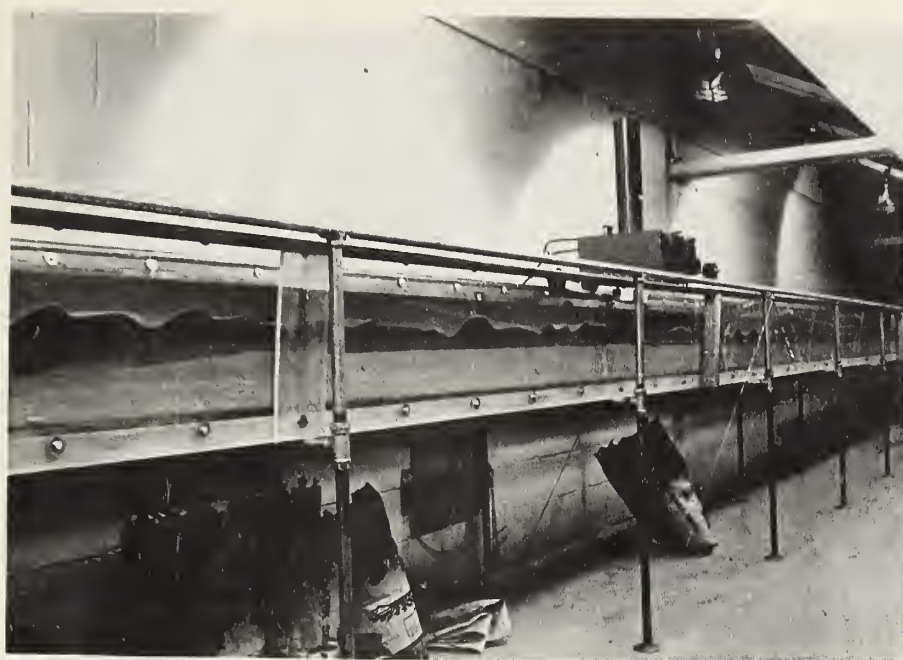


PLATE 3. VIEW OF THE MEASURING APPARATUS



PLATE 4. ILLUSTRATION OF DIFFERENTLY COLOURED SAND INTERFACES AFTER FIRST AGGRADATION RUN

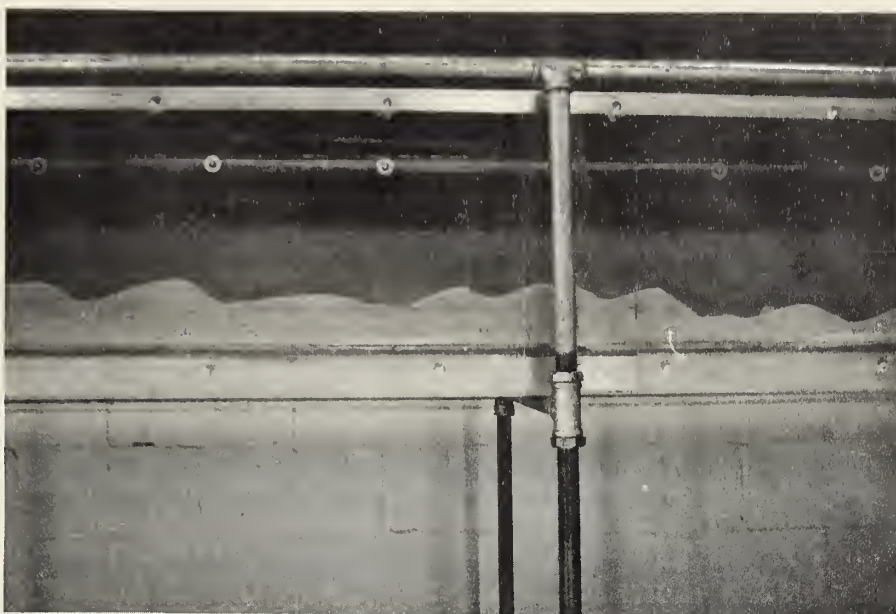


PLATE 5. CLOSE-UP VIEW OF SEDIMENT WAVE FRONT



PLATE 6. ILLUSTRATION OF DUNE FORMATION OF BED,
LOOKING DOWNSTREAM



PLATE 7. VIEW OF COLOUR GRADATION OF SAND LAYER

APPENDIX D

ORIGINAL DATA



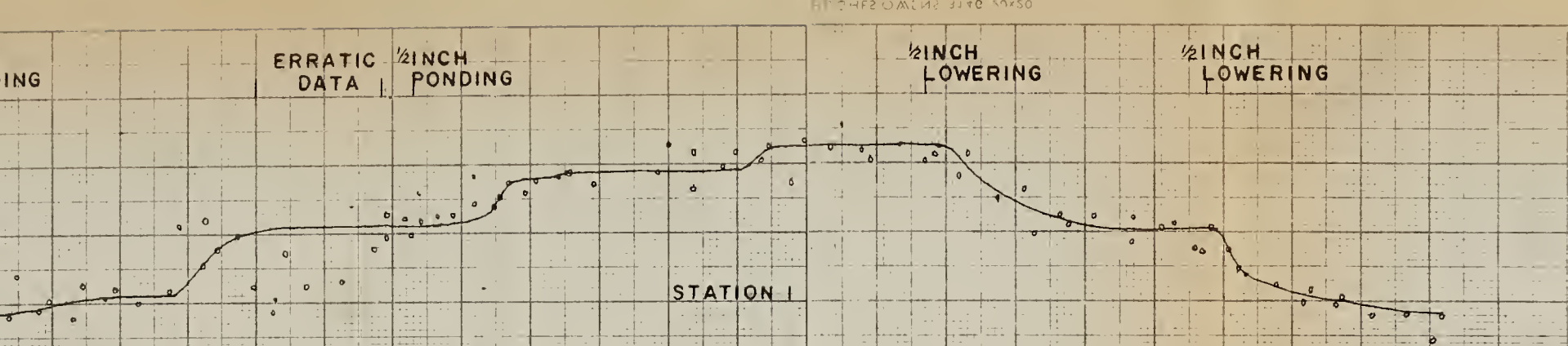
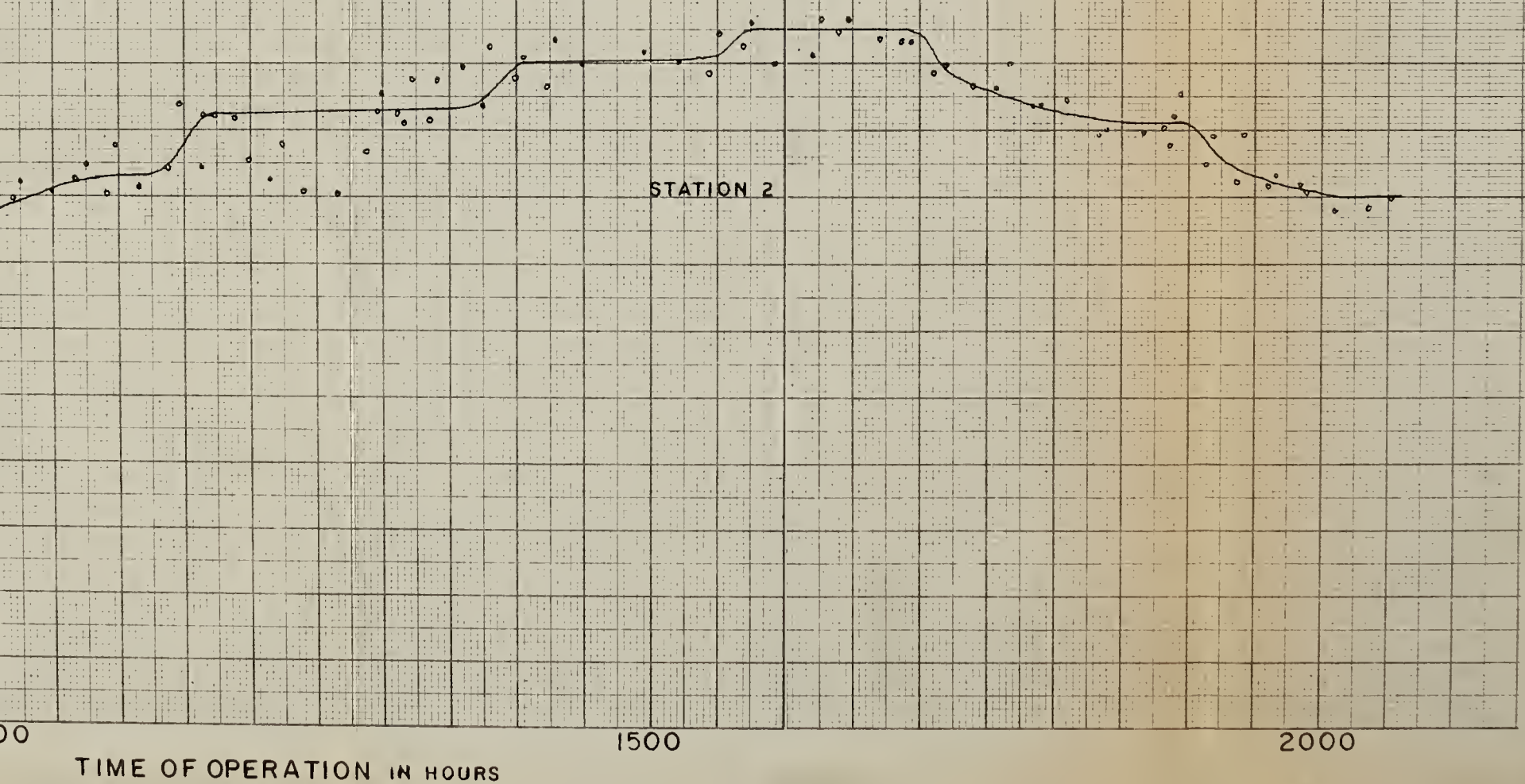


FIG. D1A
VARIATION OF BED ELEVATION
AT DIFFERENT STATIONS WITH
TIME



ELEVATION OF BED IN INCHES

7

6

5

4

3

2

1

0

0

0

0

500

1000

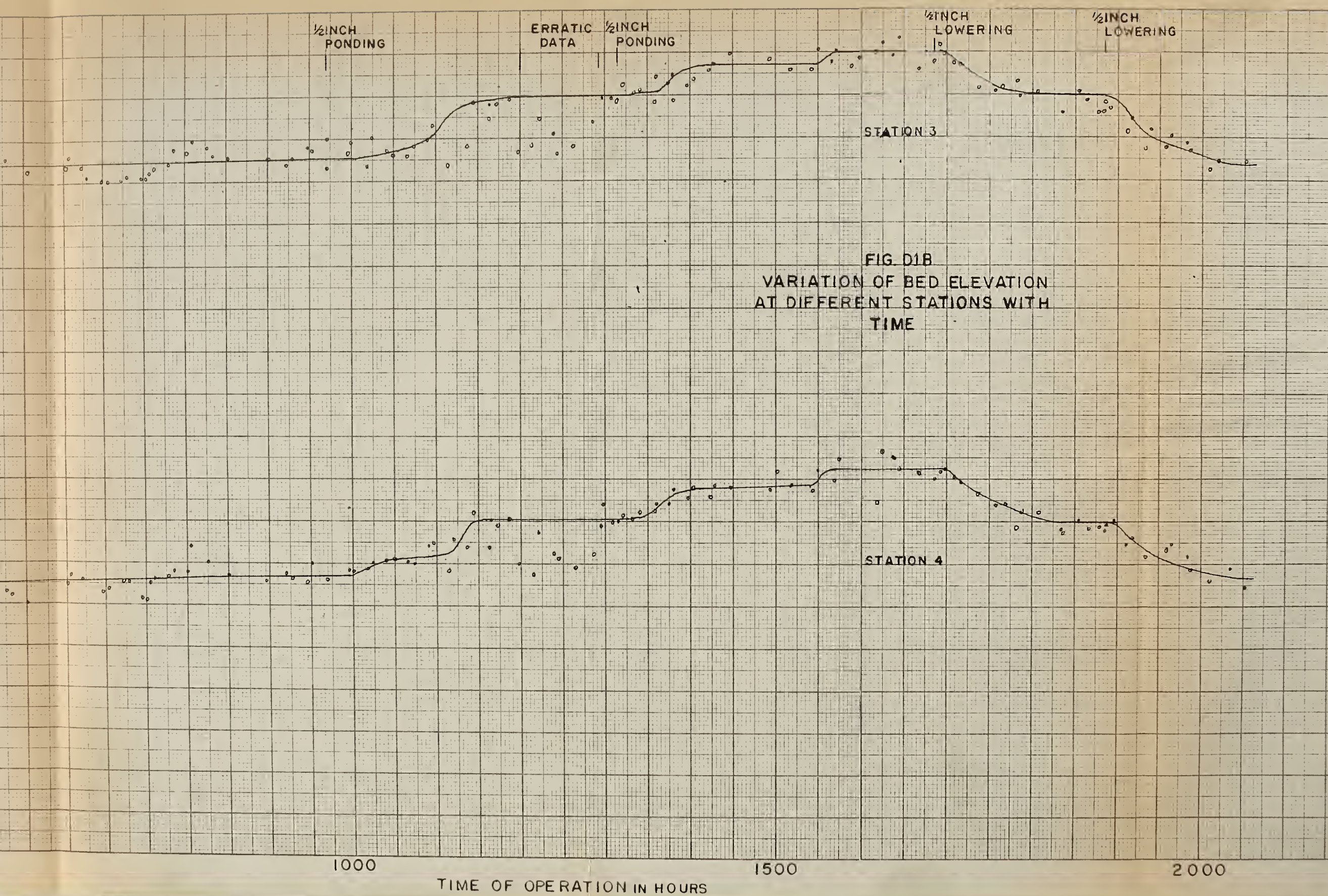
TIME OF OPERATION IN HOURS

1/2 INCH
PONDING

ERRATIC
DATA

1/2 INCH
PONDING







1/2 INCH
LOADING

1/2 INCH
LOWERING

1/2 INCH
LOWERING

STATION 5

FIG. D1C
VARIATION OF BED ELEVATION
AT DIFFERENT STATIONS WITH
TIME

STATION 6

1500

2000

ATION IN HOURS

ELEVATION OF BED IN INCHES

0

2

3

4

5

2

3

4

5

500

1000

1 INCH
PONDING

1/2 INCH
PONDING



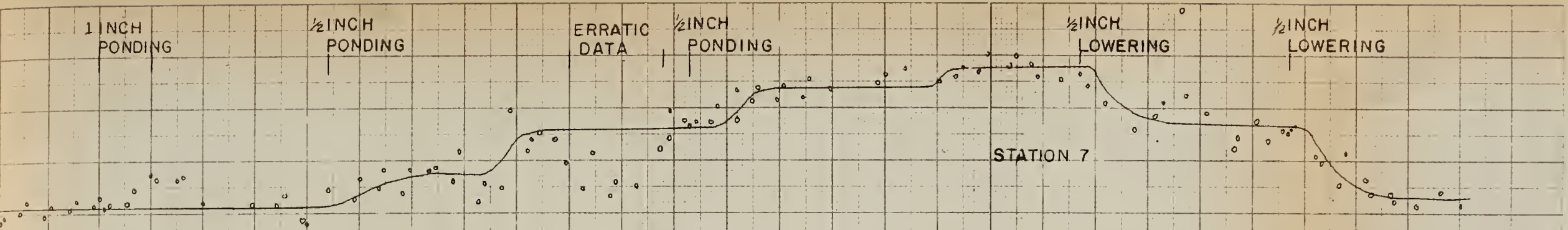
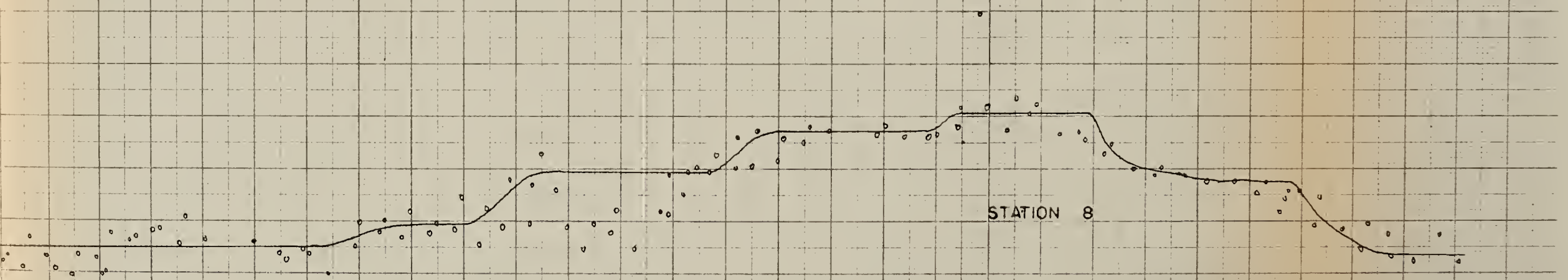
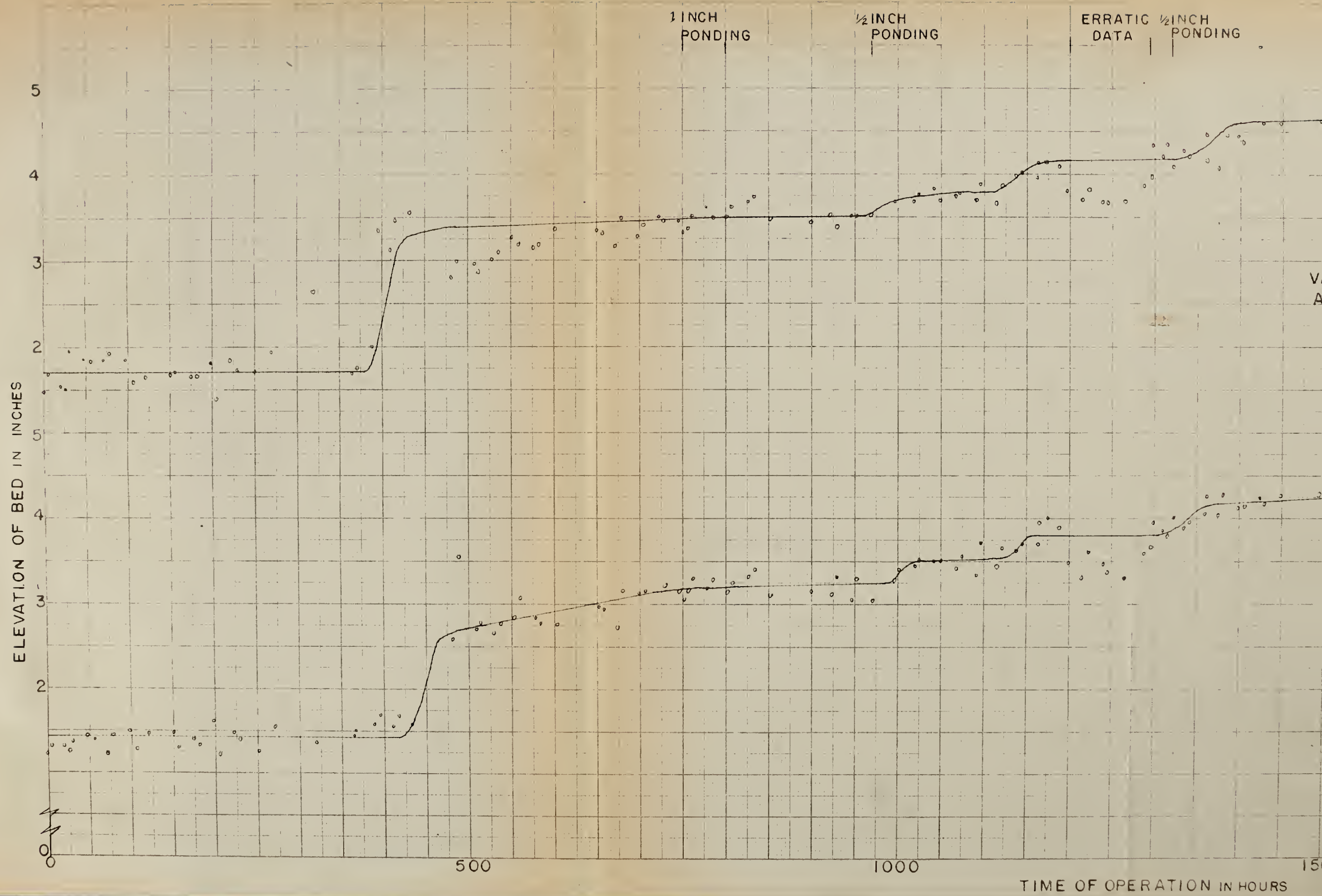


FIG. D1D
VARIATION OF BED ELEVATION
AT DIFFERENT STATIONS WITH
TIME





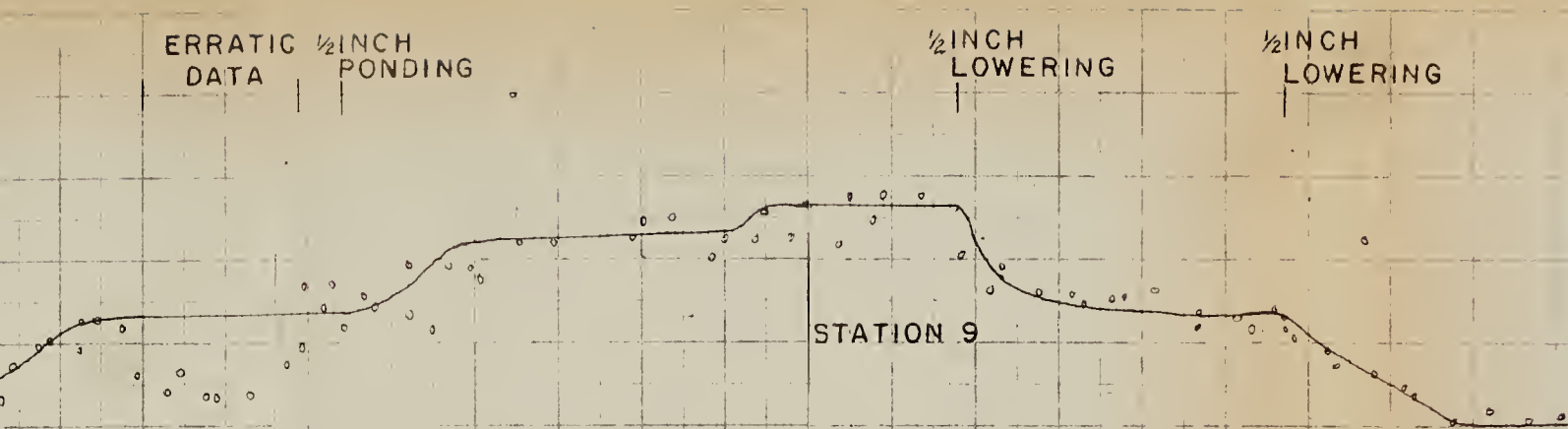
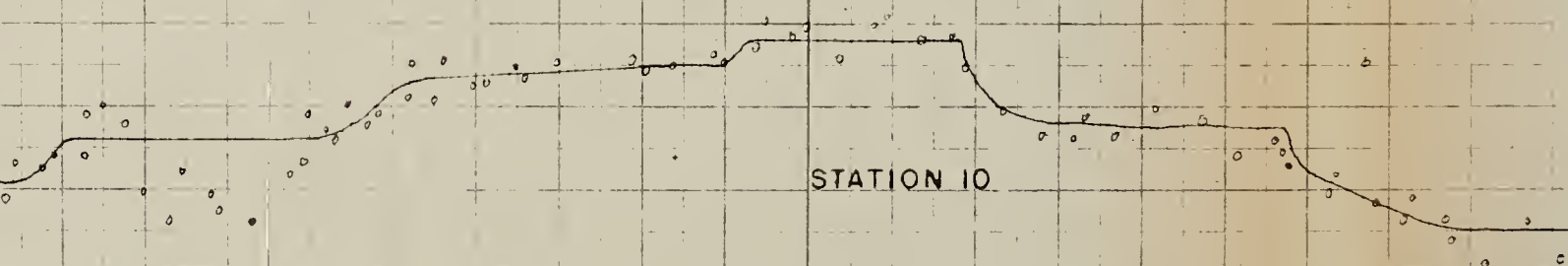
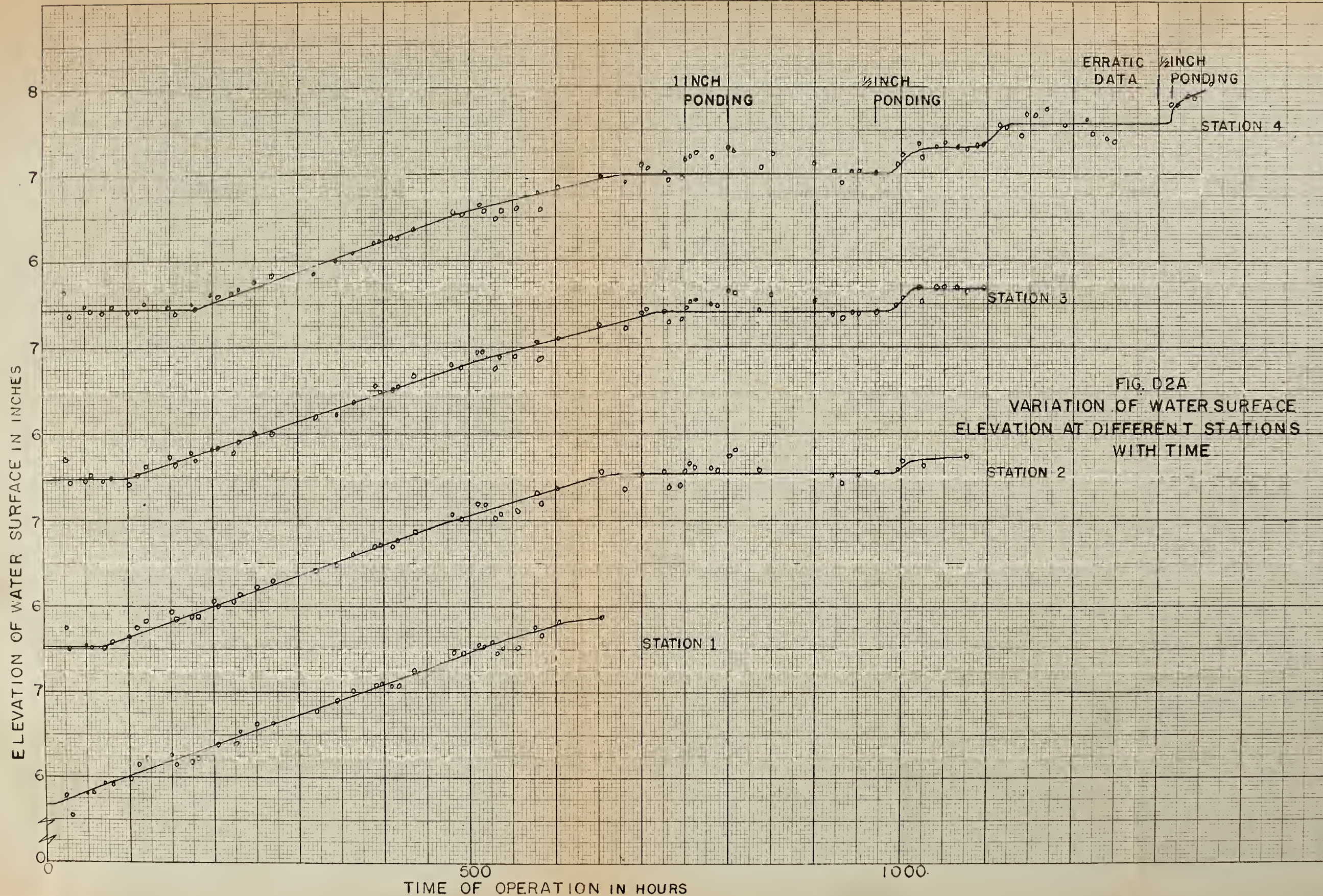


FIG D1E
VARIATION OF BED ELEVATION
AT DIFFERENT STATIONS WITH
TIME



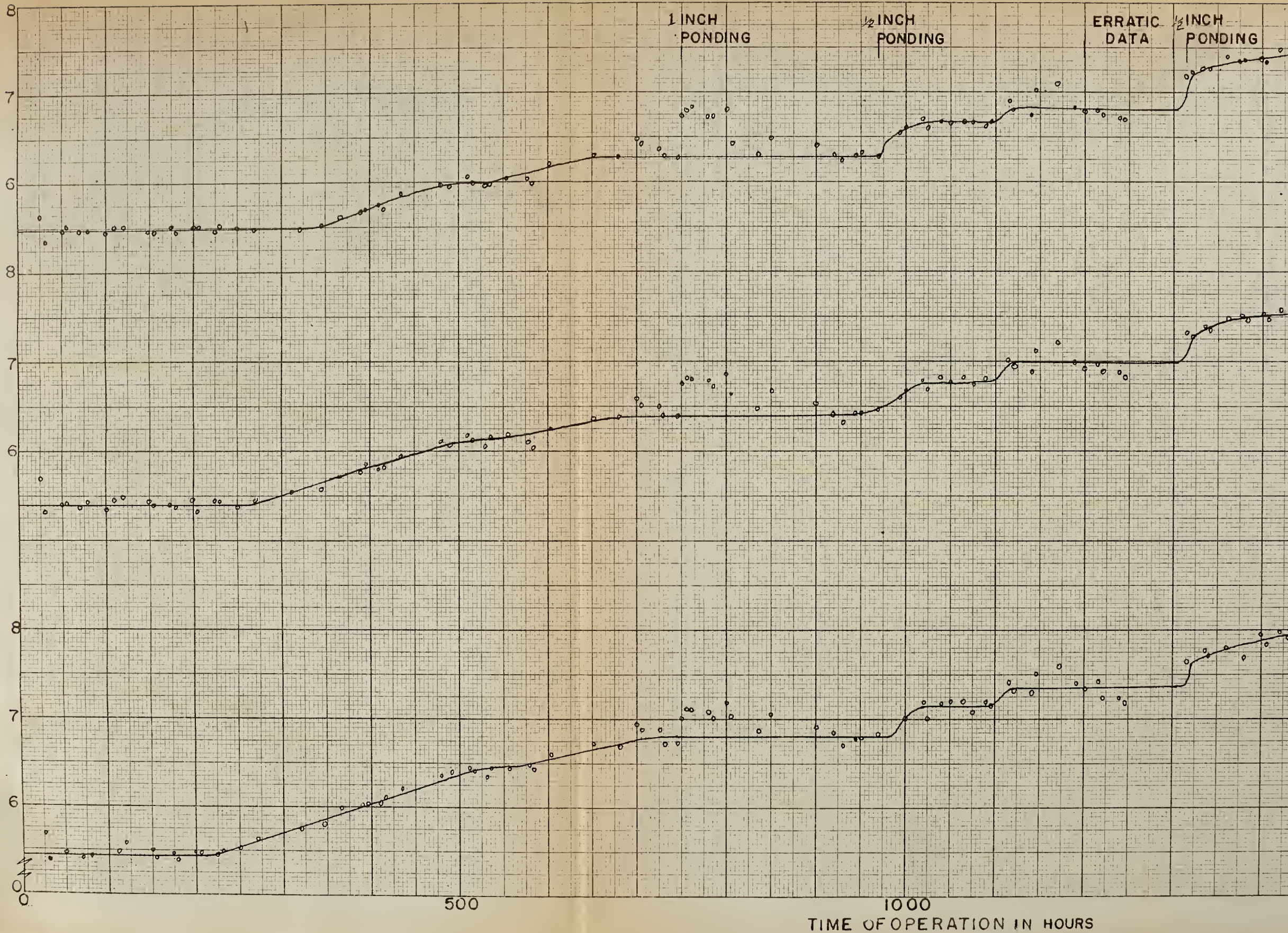
1500 2000

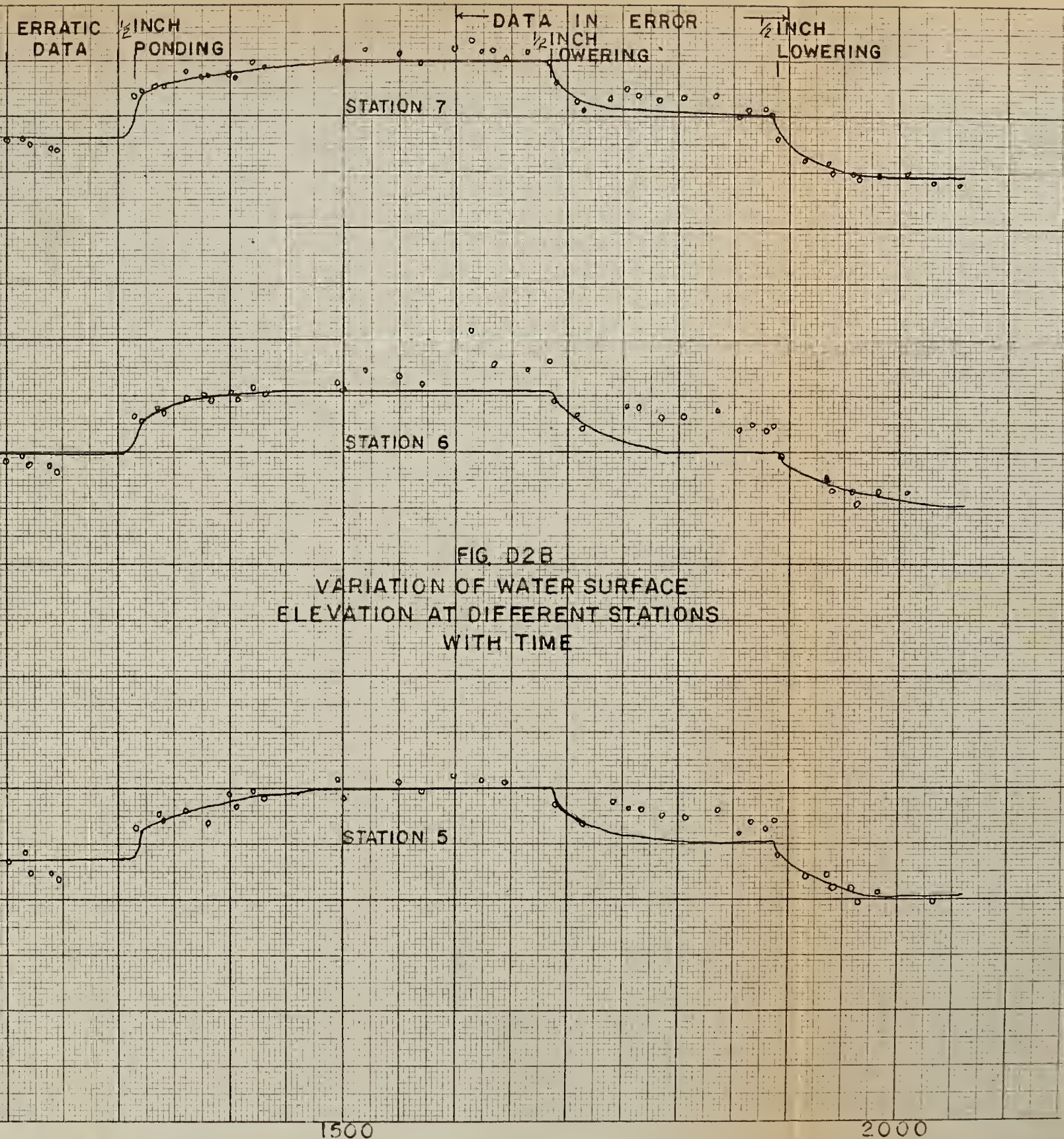
TIME OF OPERATION IN HOURS



K&E
10 X 12 INCHES
KENTLETT & EPPER CO.
50 X 50 TO THE INCH
MADE IN A.S.T.V.
41 1545

ELEVATION OF WATER SURFACE IN INCHES





K&E
10 X 12 INCHES
KENTLETT & EPPER CO.
50 X 50 TO THE INCH
MADE IN U.S.A.
47 1545

ELEVATION OF WATER SURFACE IN INCHES

1 INCH
PONDING

1/2 INCH
PONDING

7

6

5

7

6

5

7

6

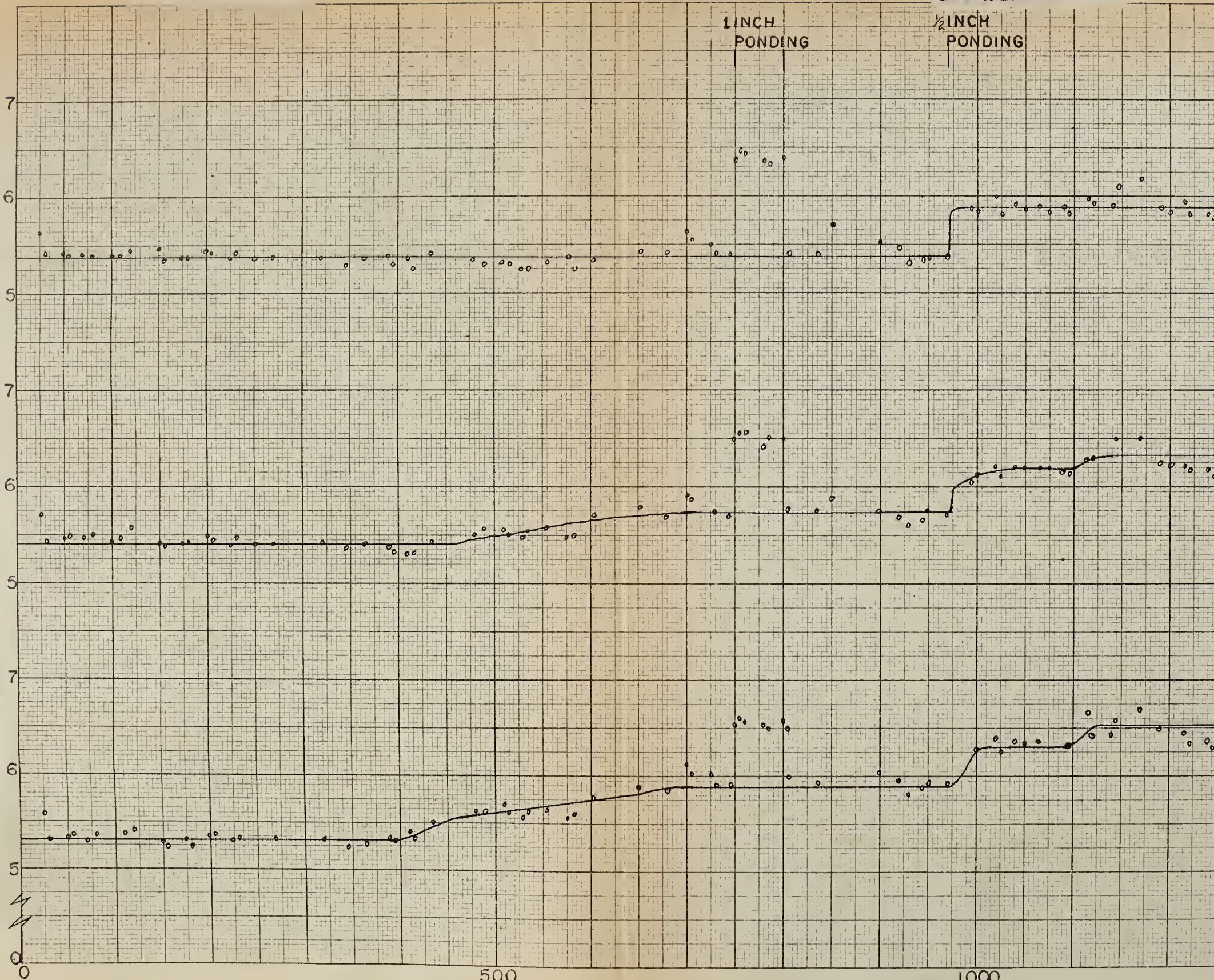
5

4
3
2
1
0

500

1000

TIME OF OPERATION IN HOURS



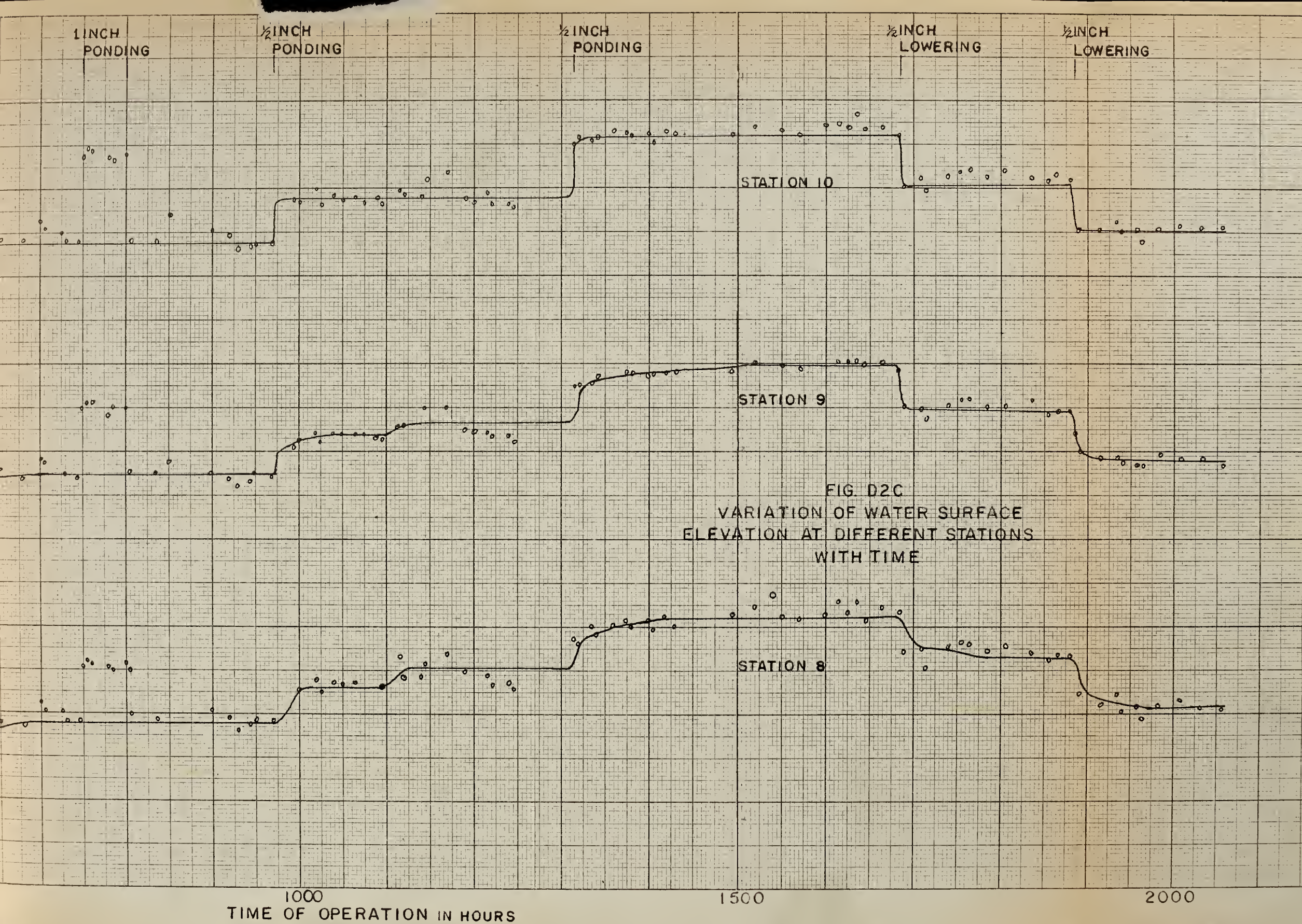


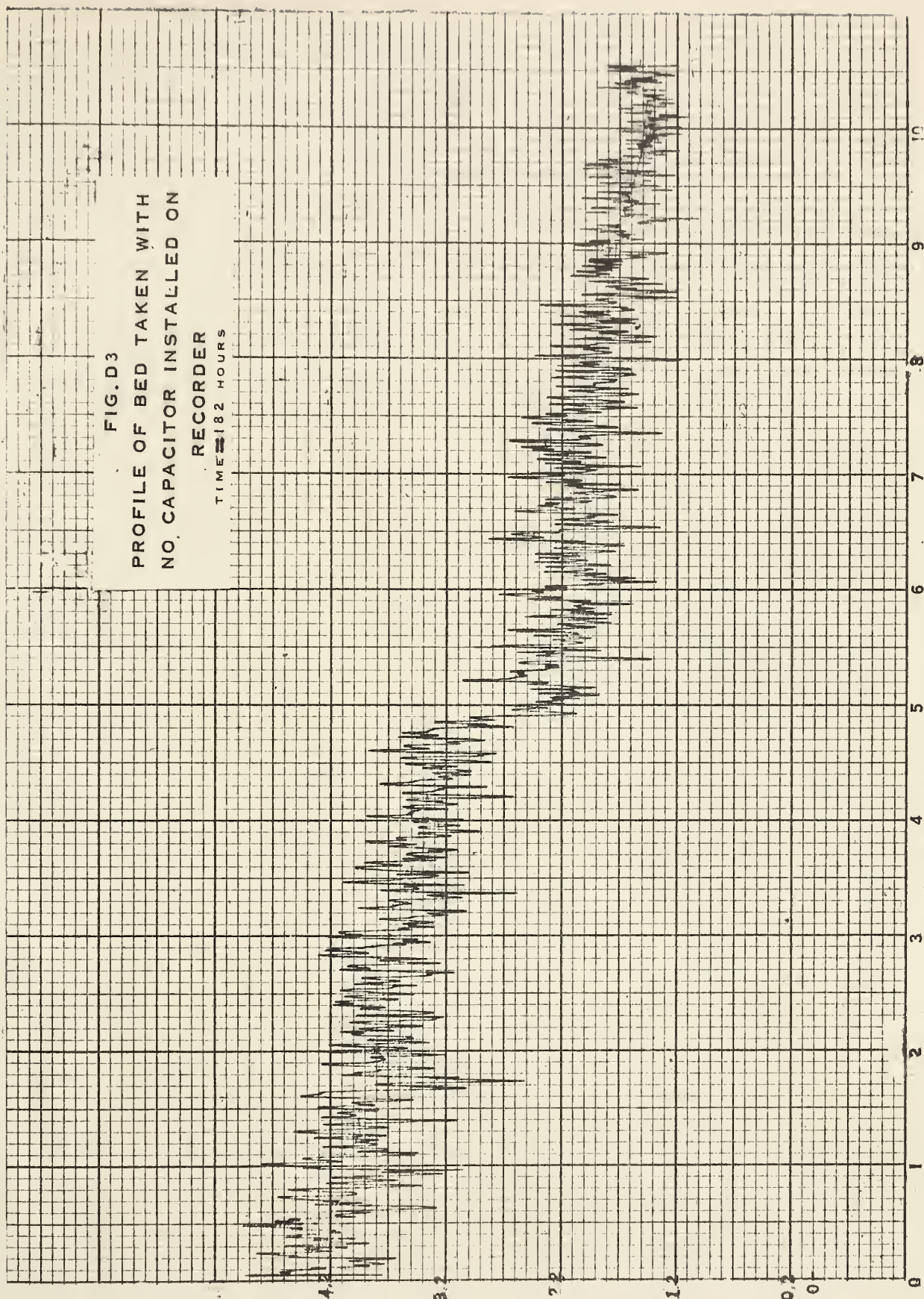
FIG.D3

PROFILE OF BED TAKEN WITH
NO CAPACITOR INSTALLED ON
RECORDER

TIME 182 HOURS

ELEVATION OF BED IN INCHES

DISTANCE DOWNSTREAM-STATIONS AT 10 FT. INTERVALS





B29848